THE OCCURRENCE OF FRESH WATER ON SMALL OCEANIC ISLANDS

by

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INTRODUCTION

In the 121 million square miles of deep salt water comprising the Pacific, Atlantic and Indian Oceans lie thousands of small isolated islands. The total dry land area of these islands is almost insignificant, probably less than one-tenth of one per cent of the ocean area in which they exist, yet they have been of immense importance to man in his conquests of the lands beyond the horizon. Of the many hopes that the oceanic island represented to the mariner of old, none was more primary, or probably more prayed for, than the finding of what he called "sweet water." The search for fresh water on the oceanic island has presented an interesting and sometimes final challenge to men for many centuries. Today, because of the availability of direct sea water conversion techniques, the need to find fresh water in a naturally occurring state is generally less urgent; however, it is still of significant importance, and is certainly no less interesting.

The occurrence of fresh water on the small oceanic island depends principally on the geologic, geomorphic, and climatic characteristics of the island. Islands may be mountains rising into the clouds, or low flat landmasses barely emerging above the sea; they may support a rain forest or a desert, or even both on the same island; they may be unbearably cold or uncomfortably hot, even with the moderation of temperature characteristic of their oceanic situation; and they may be almost continuously shrouded with fog or perpetually bathed in sunshine. The exact hydrological nature of each island is a unique determination by many natural controls and influences.

The term "small" island is defined to include those islands generally less than 500 square miles in area. Excluded then, are the large islands such as Iceland and Hawaii which are truly oceanic, but which are hydrologically similar to continental situations. "Oceanic" islands are considered those which rise from the deep ocean floor independent of the continents. The islands analyzed herein are those which are generally free from continental influences of both geology and climate. These oceanic islands are the andesite volcanic islands of the festoon of the circum-Pacific "ring of fire" and the island arc of the Lesser Antilles in the Carribean, and the basalt volcanic islands of the mid-ocean ridges or swells. In some instances, where of value in gaining better understanding of the oceanic island situation, non-oceanic islands are discussed in part on specific points, but it is not intended to cover such islands in a complete discussion.

As Le Grand (1962) has pointed out, hydrogeologic situations are usually someplace in between two extremes:

1. that each situation is completely different requiring a special study to develop a solution.
2. that all situations are the same eliminating the need for future study after the first solution.

It is readily apparent that in actuality the solution to the situation will require both past knowledge and new study in some combination. A reasonable approach is the use of analog expression, the development of a generalized hypothetical condition to which specific field conditions may be related. Such analogies are limited in providing specific solutions, but they serve as guides to future work and give understanding to the basic

problem and hydrologic setting. With this purpose intended, the latter part of this paper represents a consolidation of available pertinent information into several generalized type situations. The information utilized generally is that of published literature supported in part by direct correspondence with concerned parties at island locations.

In order to provide a basic understanding of the subject material, and achieve the stated purpose, the discussion which follows is by sections in sequence as indicated below:

1. Geologic/geomorphic origin and nature of oceanic islands.
2. Climatic features of the oceanic environment.
3. Vegetation of oceanic islands in terms of distribution and influence on the occurrence of fresh water.
4. Fresh water-sea water relationship as a phenomena of special importance in the small oceanic island.
5. Generalized hypothetical model descriptions of the occurrence and primary utilization of fresh water on each of several basic island types. As a part of this section descriptions of the hydrological features of specific real islands representing each type are provided.
6. Conclusions and recommendations for further study.

The first four of these sections are devoted to the principal factors which determine the hydrologic nature of the island. Section five interrelates these factors to the specific hydrologic situation of each type island.

GEOLOGY OF OCEANIC ISLANDS

General Nature and Origin

Oceanic islands rise directly from the deep ocean floor as opposed to continental islands which may be emerged portions of a continental landmass or be developed on a continental basement. The primary mechanism of emergence of the parent landmasses of oceanic islands has been volcanism. Volcanic action has pushed tremendous quantities of rock from the ocean deep through some 12,000 to 18,000 feet of water to emerge above sea level. In addition to this, the subaerial elevation of such a mountain island may be many thousands of feet. One of the finest and best known examples of this is the Island of Hawaii where snow capped Mauna Kea and Mauna Loa mountains stand respectively 13,784 feet and 13,679 feet above sea level rising from an ocean depth of over 15,000 feet (Putnam 1964).

An important geologic characteristic of deep ocean basins is that the sialic or granitic rock layer found on continents is generally missing. Instead, the ocean floor seems to be made of the darker, heavier, simatic rock which underlies the sial layer on continents. Overlying the ocean floor is a covering of deep sea sediments several thousand feet thick. Accordingly, one of the features most indicative of oceanic island volcanic rock formations is the lack of sialic magma derivatives (Leet and Judson 1958), and predominance of the andesitic and basaltic types. The origin and characteristics of the oceanic coral atoll or limestone island will be discussed in detail later.

The islands considered herein may emerge from the more central parts of the oceans, the deep basins; or they may rise from the periphery of those basins in long sweeping island arcs. The mid-oceanic islands, such as the Hawaiian Islands, the Line Islands, the Marshall Islands, Samoa Islands, and Marquesas Islands, all of the Pacific, and the Azores and Tristan da Cunha Islands of the Atlantic rise in groups from swells or ridges. This type of island with its dominant basaltic rocks, is separated from the landward more acidic rocks by an "andesite line" in the Pacific Ocean according to Hamilton (1956). The andesite line runs from the Aleutian Islands of the North Pacific to the Japanese Archipelago, the Mariana Islands, the Palau Islands, the Bismarck Archipelago, then south, running east of New Zealand via the Fiji and Tonga Island groups (Plate I). On the east side of the Pacific the "andesite line" runs along the continental margins of the Americas, west of the California islands. Such a geologic division has not been made in the Atlantic; however, it appears that the rocks of the central islands of the Atlantic are predominantly basaltic, while the few examples of circumbasin islands, such as the Lesser Antilles are predominantly andesitic. In fact basaltic rock is found on the Atlantic Ridge itself, and it looks as if the ridge is a pressed-up part of the basaltic substratum of the Atlantic Ocean floor (DeSitter 1956). In all the oceanic islands metamorphic and sedimentary rocks, common continental occurrences, are rare.

One of the most conspicuous features in the structural pattern of the circumbasin islands is the occurrence of the island arc configuration. These arcs seem to lie almost exactly on the border of the continental sial

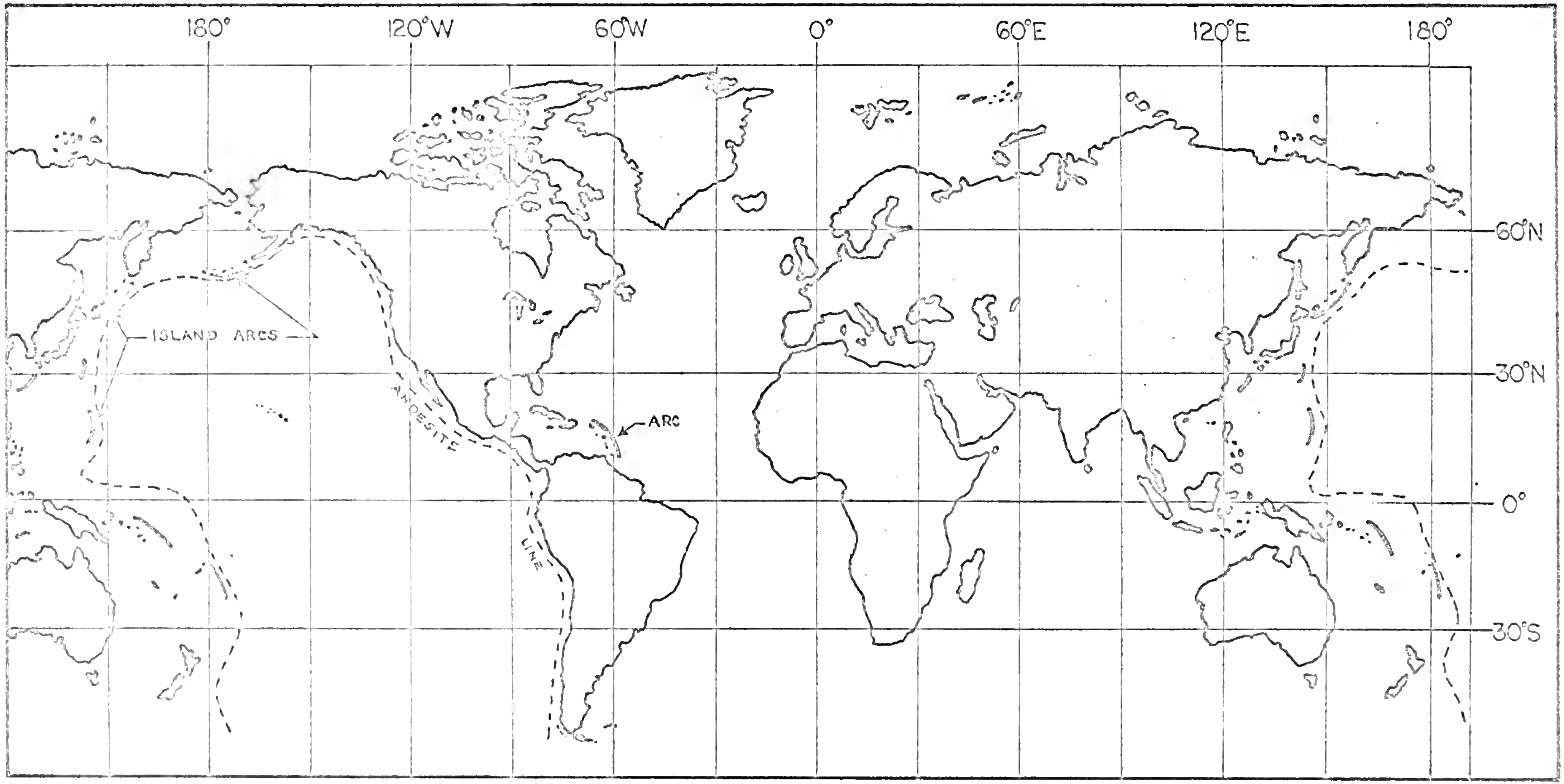


PLATE I THE ANDESITE LINE AND ISLAND ARCS

INFORMATION FROM DESITTER (1956)

crust and the mid-ocean sima crust, just inside the andesite line separating the basaltic islands from the andesitic islands as shown in Plate I. The island arcs are chiefly of andesitic rock. The orientation of each arc is with convex side facing the open ocean as well-demonstrated by the Aleutian and Marianas arcs of the Pacific and the Lesser Antilles arc of the Atlantic (Carribean). A deep oceanic depression invariably accompanies the arc on their convex or ocean side. Large gravity anomalies, volcanism, and great seismic activity are present in island arc regions.

One of the best substantiated theories of arc development is that the volcanic belt is caused by a thrust movement of a marginal geanticline of the continent over the ocean floor with a dip of about 50° toward the continent as illustrated in Figure 1 (DeSitter 1956).

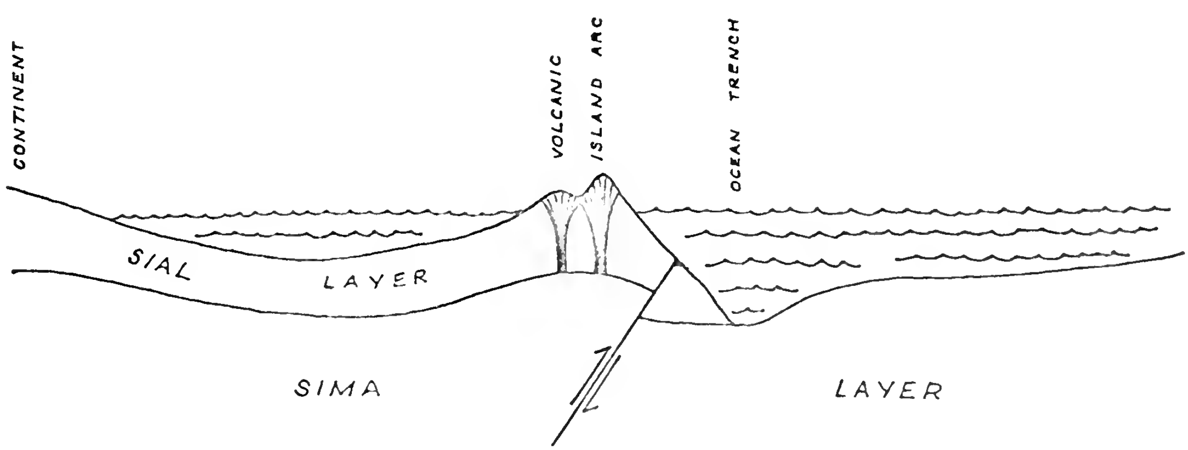


Figure 1. Island Arc Thrust Theory

Extrusion of magma took place through the fractured sial layer of the upthrust crust according to the theory.

Island Stability and Durability

The volcanic oceanic island is a relatively unstable structure, but is, by comparison with most continental features, rapidly changing. From the island's first emergence the ocean begins to tear it away again; concurrently climatic elements begin their attack. Additionally, structural instability may cause the island to rise or sink, seismic activity may cause extensive faulting, and renewed volcanic action may destroy, efface, or add to the island. The more indirect features of the ocean, eustatic change of sea level and the growth of reef coral may also play important parts in the physical features of, and duration of the oceanic island.

Around all except the most recent oceanic islands is found a submarine bench or shelf; in some locations this shelf alone may remain as the final result of planation by oceanic and climatic erosional forces. These shelves may in many instances represent a more complicated history than simple planation, but it is apparent that an island which remains stable for a relatively long period of time will in the end be eroded close to sea level. Beach materials act as abrasives; without this, wave action on hard rock material is relatively ineffective. The notch frequently seen at the base of a sea cliff is the mark of the sea cutting into the island, but does not usually develop where the cliff falls into deep water thus prohibiting the accumulation of abrasive material (Russell 1963).

When an island is high, climatic factors play an increasingly greater part in the reduction of the island. Most oceanic islands over 2000 feet high induce a large amount of rainfall (frequently greater than 70 inches per year) at their summits; this feature, combined with rapid decomposition

of hard rock to friable soil in the humid atmosphere readily erodes and transports the high level material to the sea.

Movement of the island after development, or movement of sea relative to the island, is frequently evident from the existence of physiographic features inconsistent with the present sea level. Some of these features such as the elevated shorelines (marine terraces) of San Clemente Island and the coral reef remnants of Guam, in both instances lying well over a thousand feet above sea level, are too great to be accounted for by probable eustatic sea level change during the Pleistocene, but must be evidence of great uplift of the landmass. Other islands, such as Antigua in the Lesser Antilles, display obvious tilting as indicated by the dip of strata originally laid level (Davis 1926). Stearns (1945) states that a great subsidence of the Pacific Basin of as much as 10,000 feet took place in late Pliocene or early Pleistocene time. While this amount at that period remains to be fully proven, the finding of guyots, assumed to be truncated submerged islands, and seamounts (which may be submerged peak islands) some 3000 to 6000 feet beneath the sea indicates that great subsidence has taken place in the past. Fossil coral has been found on some guyots indicating submergence in the Cretaceous Period, over 70 million years ago (Putnam 1964). Davis (1924) states that a prevailing feature of volcanic islands is that they are unstable, and exhibit a decided tendency to subsidence.

Current volcanic activity is directly observable on many oceanic islands. This activity may range from the existence of the numerous thermal springs of San Miguel in the Azores to the spectacular "quiet" lava flows of Hawaii. The results of this volcanic activity may be the

covering of old eroded surfaces by new volcanic products of lava, pyroclastics, or ash deposits. Heavy ash fall may significantly affect other islands in the proximity as it has frequently in the Aleutian Islands (Fraser and Snyder 1959). Probably the most dramatic complete destruction of an island by its own activity in recent times was when the 2600 foot high Island of Krakatoa in the East Indies disappeared in 1883. After the incredible violence had subsided, the mountain island was completely gone and a 1000 foot deep submarine caldera existed in its place (Putnam 1964).

On a world-wide basis perhaps the most significant morphological effect of all on oceanic islands has been the fluctuation of sea level due to Pleistocene glaciation. Eustatic fluctuation of sea level by glacial control, first recognized in 1842, is an accepted theory. The chief difficulty is reducing the fluctuations to a quantitative basis. Past glaciation has been both greater and lesser than that today. Deductions from the calculated ice volume at a glacial maxima indicate that the sea level could have stood from 300 to 480 feet below its present sea level. During warm interglacial periods glacial melt water probably raised the sea level at least 25 feet higher than the present. If all the glacial ice were to melt today sea level would be raised between 100 and 200 feet (Flint 1957). Evidence is overwhelmingly in favor of a general rise of sea level extending from about 20,000 years to 3000 years ago (Shepard 1963). Contemporary rise of sea level as observed along the United States Atlantic and Gulf coasts is about 1 foot per 100 years between AD 1650 and 1950 and 1/2 foot per 100 years between 4500 BC

and AD 1620 (Flint 1957). Putnam (1964) cites the apparent rise since 1890 AD as 4-3/4 inches per century. Embayed coastlines and drowned valleys are a common, but significant, result of the rise of sea level in recent times. It is of importance to note that there were at least four major glaciations during the approximately 1,000,000 years of the Pleistocene with the last reaching a maximum as recently as 18,000 years ago. With each glacial cycle there were very significant eustatic sea level changes.

In those regions actually overridden by the several thousand feet of glacial ice, postglacial uplift of land is taking place. The great weight of the ice mass, as much as 100 tons per square foot, depressed and compressed the land on which it lay. With the recession of the ice, this overburden melted away, and rebound began. Uplifted wave-cut features in Scandinavia show that the central part of the peninsula has risen 800 feet or more since the glacial ice receded. The land rise is still continuing at the rate of about three feet per hundred years at the head of the Baltic Sea (Putnam 1964). Postglacial rebound of about 700 feet has been reported for the Canadian Arctic islands in the past 7500 to 9000 years (Shepard 1963).

Coral Reefs and Atolls

One of the most challenging and intriguing geological questions of the past century has been that of the origin of the coral atoll. Throughout the tropical waters are found what are romantically called "garlands of white strewn on a blue sea." Actually the coral atoll is a physiographic

structure composed basically of coral reef, broken reef rock, and coral sand; it rises abruptly from the ocean depths and typically encloses a shallow lagoon in its center as shown on Plate II. The outer wave-washed rim of the atoll has a configuration which is frequently angular or elliptical. The entire atoll may be awash or submerged with no dry land, or may be raised to a height such that the lagoon basin is dry (Fosberg and Sachet 1953). Low islands of coral and sand are formed or destroyed on the atoll rim when storm waves pile up reef fragments above sea level.

There are at least 330 atolls in the world with only about 10 lying outside the Indo-Pacific tropical area. Among these exceptions are Midway in the Central Pacific, the Dry Tortugas (west of Key West, Florida) and Hogsty Reef in the Bahamas (Shepard 1963). The largest emergent atoll is Kwajalein in the Marshall Islands of the South Pacific. It is 75 miles long and as much as 15 miles across; most atolls are much smaller (Putnam 1964). According to Gardiner (1931) the term atoll is derived from the language of the Maldive Islands in the Indian Ocean. Each governmental district in the Maldive Island group is termed an atolu; each atolu province being a ring of coral islands surrounding a great central lagoon, a configuration now called universally an atoll.

The unique feature of atolls which provided the barrier to a ready solution to the question of origin is that the foundation on which the coral grows is not exposed. The same reef corals may grow also as a fringing reef directly on an island as on Raratonga Island, or as a barrier reef offshore enclosing a lagoon between the reef and interior volcanic island(s) as at Truk (Wiens 1962). The relation of these occurrences of reef coral to the development of an atoll is not quickly

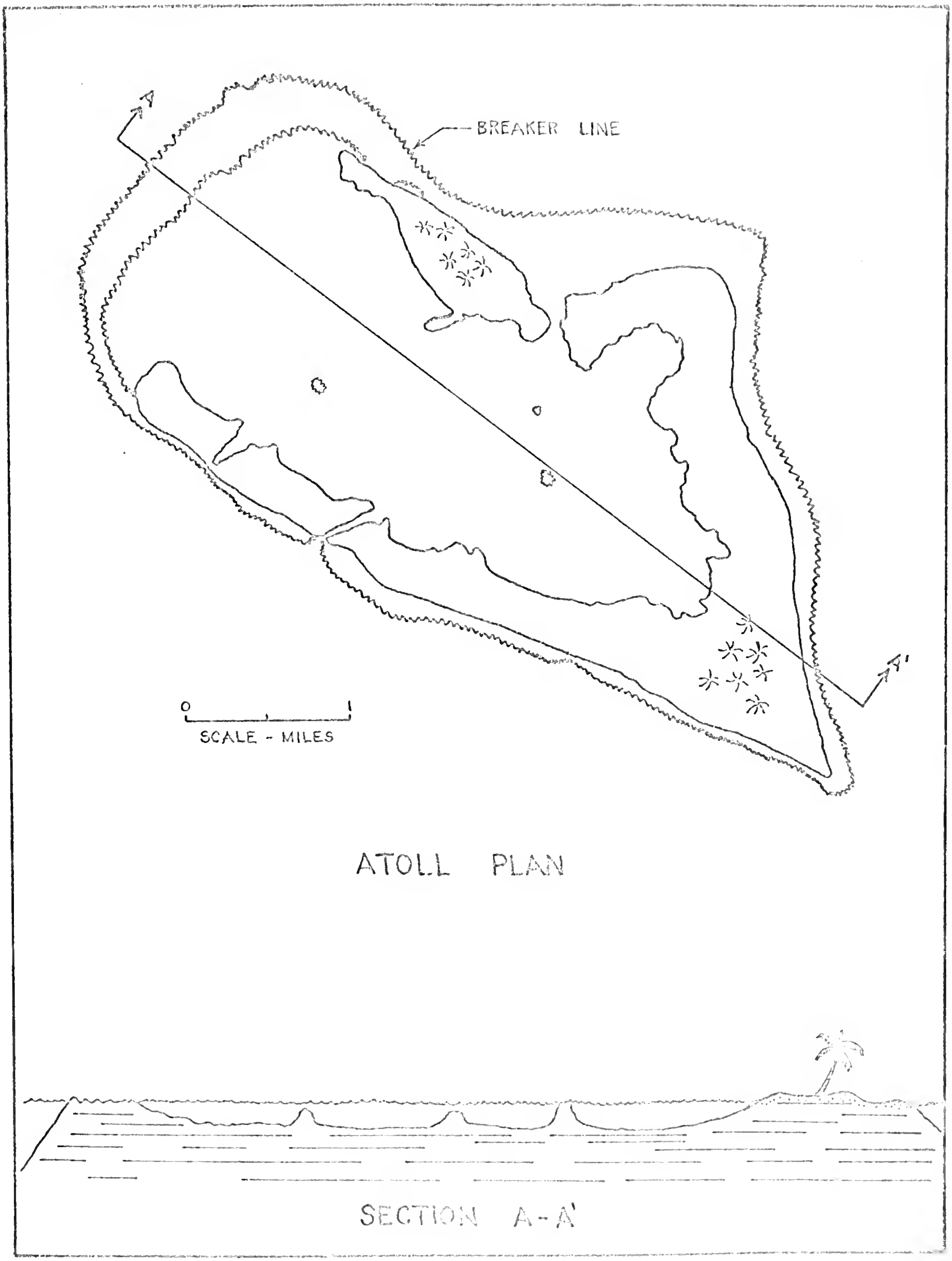


PLATE II THE TYPICAL CORAL ATOLL

explained, however. Since 1821, ten principal theories have been offered for the formation of atolls, the most famous being Charles Darwin's "subsidence theory" published in 1842. Darwin's theory is not only the one which, in the light of the most recent scientific information, seems to be most generally correct, but is all the more remarkable since he developed it with limited scientific observation as a young man of twenty-two (Fosberg and Sachet 1953). The most serious deficiency of Darwin's original theory is its failure to recognize the profound influence of glaciation on the level of the sea.

Before proceeding with what seems today to be the most plausible explanation of the occurrence of coral reefs and atolls, the several generally accepted facts as stated in part by Stearns (1946) will be given.

1. Reef building corals thrive only at moderate depths (usually less than 200 feet) in warm (between 77° and 86°F) clear water of normal salinity (between 27 and 38 parts per thousand). The limits of the present growth of reef coral is shown on Plate III.

2. Calcarious algae lives in a symbiotic relationship with the coral and contributes a hard durable binder to the reef structure.

3. Sea level was in the order of 300 feet lower during several glacial stages of the Pleistocene.

4. Coral atolls probably rest ultimately on basements of non-coraliferous rock as demonstrated by

    a. basement rock basalt encountered at Eniwetok Atoll in two holes at depths of 4158 and 4610 feet;

    b. basement rock basalt found at Bermuda at depth of 560 feet.

5. Barrier and fringing reefs may build on a gently sloping shelf of any origin.

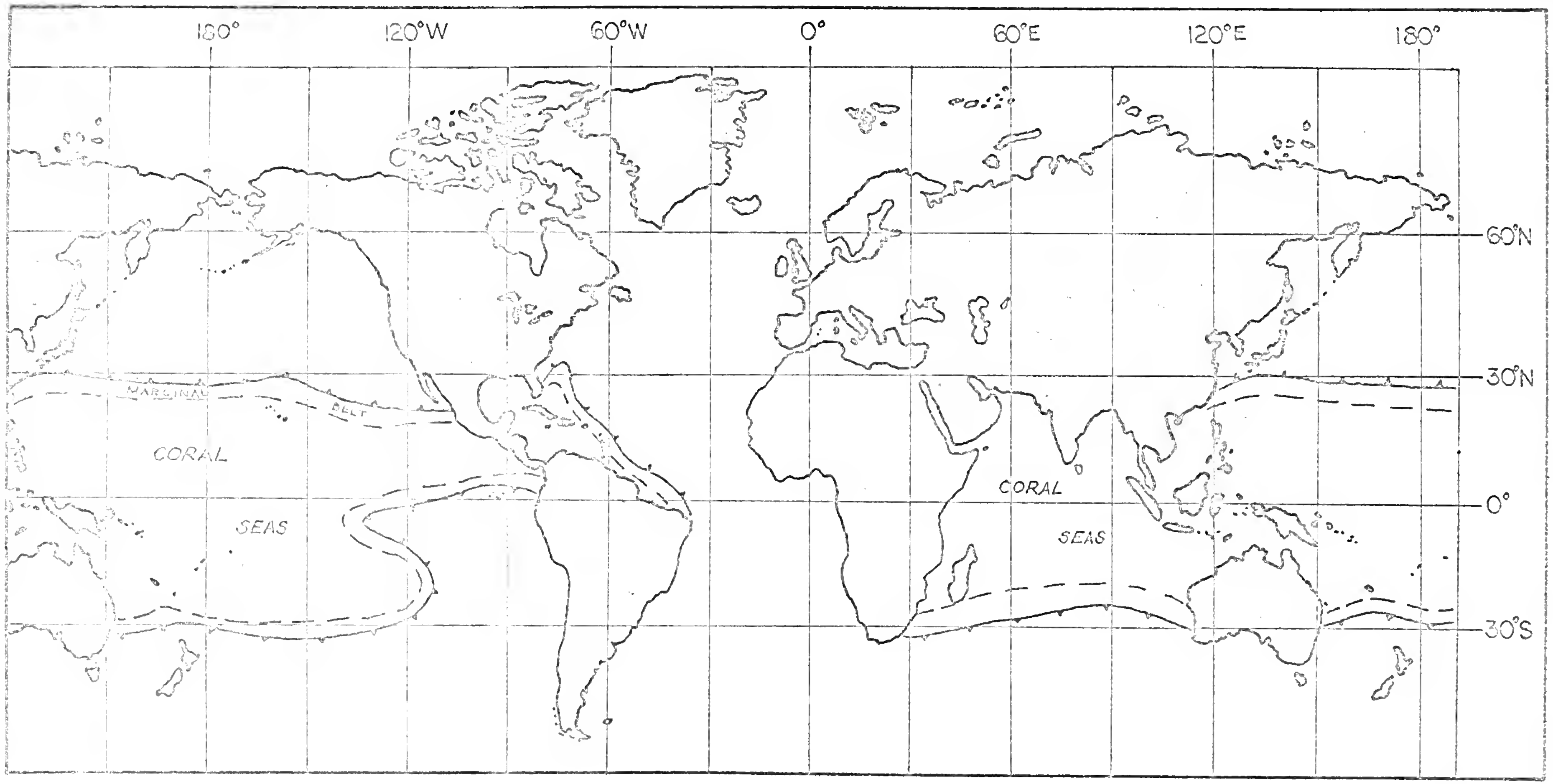


PLATE III LIMITS OF REEF CORAL GROWTH

INFORMATION FROM DAVIS (1926)

6. Coral reefs may grow upwards as rapidly as 114 feet/1000 years for corals of the reef margins and 57 feet/1000 years for those of the lagoons (Shepard 1963).

7. Rapid submergence or emergence may kill a coral reef.

8. Coral reefs grow more rapidly in the vigorous action of the breaker zone.

9. Lagoon depths range down to 300 feet, but generally average about 150 feet (Shepard 1963). The largerlagoons are generally deeper than the smaller ones (Wiens 1962).

The evidence obtained to date strongly supports Darwin's original theory of atoll formation postulated in 1842 as a result of his voyages on the H.M.S. Beagle. While it is most probable that no single theory can account for all the existing atolls, it seems likely that most atolls are the result of coral growth maintaining itself on the surface of a subsiding platform. The original platform may be either a peaked volcanic island whose fringing coral reefs overgrew it as it sank, as shown on Plate IV, or a truncated island which sank slowly enough that coral growth could keep pace. Guyots and possibly seamounts (if submerged peak islands) are generally understood to be similar to the atoll foundations. But in the case of guyots and seamounts, which lie many thousands of feet below the sea, coral growth could not occur rapidly enough to prevent killing by deep submergence, or possibly could not occur at all under the water and climate conditions existing. Limited coral remnants have been found on some guyots.

The glacial-controlled fluctuations of the oceans undoubtedly greatly affected the atolls and reefs of the Pleistocene Epoch. During the glacial maxima the sea level dropped some 300 to 400 feet, allowing the atolls to emerge as relatively high coral islands (see Plate IV).

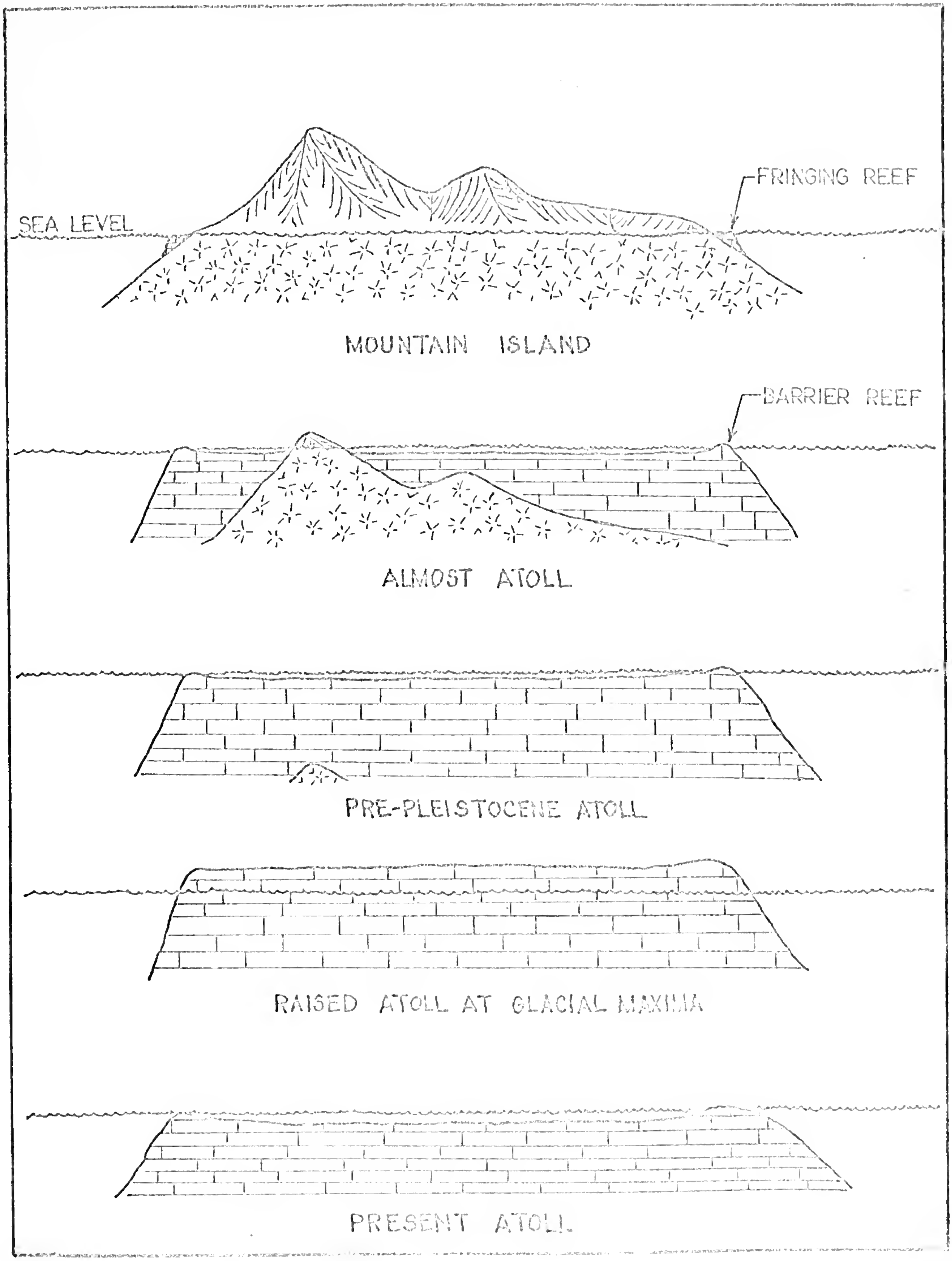


PLATE IV ATOLL FORMATION THEORY

Weathered coral rock, now submerged, contains pollen and land snails indicative of islands hundreds of feet high (Shepard 1963). The coral which emerged was killed. It was rapidly eroded and was taken into solution by rain water; in some cases probably reducing the coral island to near sea level. Subsequent rise of the water allowed regrowth of the coral, and the process of growth on a slowly, but continuously, subsiding platform was resumed to produce the low-lying coral atolls of today. The shallow lagoon is considered the result of more rapid growth of the perimeter coral than the lagoon coral. The current depth indicates both the disparity of growth since the last glacial maxima and the failure of detritus washed into the lagoon by wave action to fill it up. The lagoons in many cases appear to be filling which may indicate that subsidence has slowed sufficiently for the growth of coral in lagoons to catch up with the growth of coral on the peripheral reef.

Davis (1926) makes an important distinction between the coral reefs of the "true" coral seas and those on the margins of the coral seas. According to Davis, in true coral seas of the Western Pacific the original coral colonies never stopped growing even though those corals that emerged were destroyed; the veteran reefs of these warm waters are direct successors of ancient ancestors. On the other hand the corals of margin seas were all killed by the cooled ocean of the Pleistocene; the present novice reefs of the margin seas represent growth which has been reinstituted in postglacial times by coral larvae.

The open Atlantic is, with regard to coral reef development very similar to the eastern 3000 miles of the Pacific Ocean. In both cases the

northern and southern cool seas unite across the torrid zone, but in the Pacific another 5000 miles of equatorial breadth allow the waters to be warmed enough for coral growth, permitting a vast expanse of true coral seas. In the Atlantic the cool water occupies almost the entire equatorial width of the ocean; only in the northwestern extension of the equatorial waters in the Carribean (Cuba) are the waters warm enough for vigorous reef growth. Through the Lesser Antilles and in a long northeast loop to Bermuda a marginal belt of coral growth exists. The marginal belts of the coral seas as described by Davis (1926) are shown on Plate III.

Davis (1926) provides a very excellent discussion of the physiographic nature and origin of islands. Of the several points he makes, the most significant is that coral reefs protect the island they enclose from sea erosion. Consequently islands outside the coral seas are strongly cliffed by the sea, (such as St. Helena in the mid-Atlantic), while reef-encircled islands, (such as the Truk Islands of the Western Pacific), display very little evidence of wave cutting. There, erosion by subaerial processes predominates over marine erosion in producing the shoreline characteristics of islands of the coral seas.

Beach Rock

Beach rock occurs around many islands of the Atlantic, Pacific, and Indian Oceans and may be of considerable hydrological significance because it tends to form a sea water barrier. It is practically restricted to the intertidal zone and is composed of the basic beach

material cemented together by calcium carbonate. Beach rock may form discontinuously, but on Kwajalein Island it is of very recent origin incorporating such wartime debris as shell cases and a Coca Cola bottle.

The exact process by which beach rock is formed is not known. It is probably a result of the reduced ability of outflowing fresh water, as it becomes saline at the beach line, to hold as much calcium carbonate in solution as it could before (Fosberg and Sachet 1953).

The upper limit of cementation is set by the water table; the rock thus appears truncated because the water table is flatter than the beach angle and stratification. Beach rock is thickest where the water table fluctuates most conspicuously. When recession occurs the exposed beach rock may be high, because the water table was high. Ancient beds may exist several feet above present high tide. Since the beach rock is underlain with unconsolidated material, it may not be found where formed (Russell 1963). When first formed beach rock is soft, but exposure to the air tends to harden it (U.S. Army 1956).

Phosphate Rock

A peculiar rock formation related uniquely to the total ecological nature of an atoll island is found in the interior of some small oceanic islands. Hydrologically this rock formation is important because it may perch a water table or greatly impair downward percolation of ground water.

Generally under the Pisonia tree forests, found on some atoll islands, a layer of pure humus accumulates. These forests are normally

tremendous bird rookeries. The bird droppings (guano) are acidified by the humus as they are washed through it, and the calcium phosphate contained is dissolved. When it reaches the coral rock and sand below, the solution becomes alkaline and the calcium phosphate precipitates out, cementing the loose calcareous material together. In addition the phosphate will tend to replace the carbonate radical. Thus a cemented layer of phosphatic rock, a hard pan, is developed.

On very wet islands neither guano nor phosphatic rock is apt to occur. Thus islands with dry climates (from cool marine currents) and rich plankton life in the surrounding water favor large bird populations, and the preservation of guano. Although for this reason currently guano is produced primarily on dry islands, phosphate rock is found many times on wet islands; these deposits appear to have ancient origin (Wiens 1962).

Geoglogical Sketches of Island Groups

Lastly, with a view toward giving a brief intoduction into the specific characteristics of oceanic islands, geological sketches of selected island groups will be given.

The Aleutian Islands

The Aleutian Islands stretch in a long curving arc from the Alaska mainland for 900 miles almost to the Kamchatka Peninsula on the Asian side of the North Pacific Ocean as shown on Figure 2.

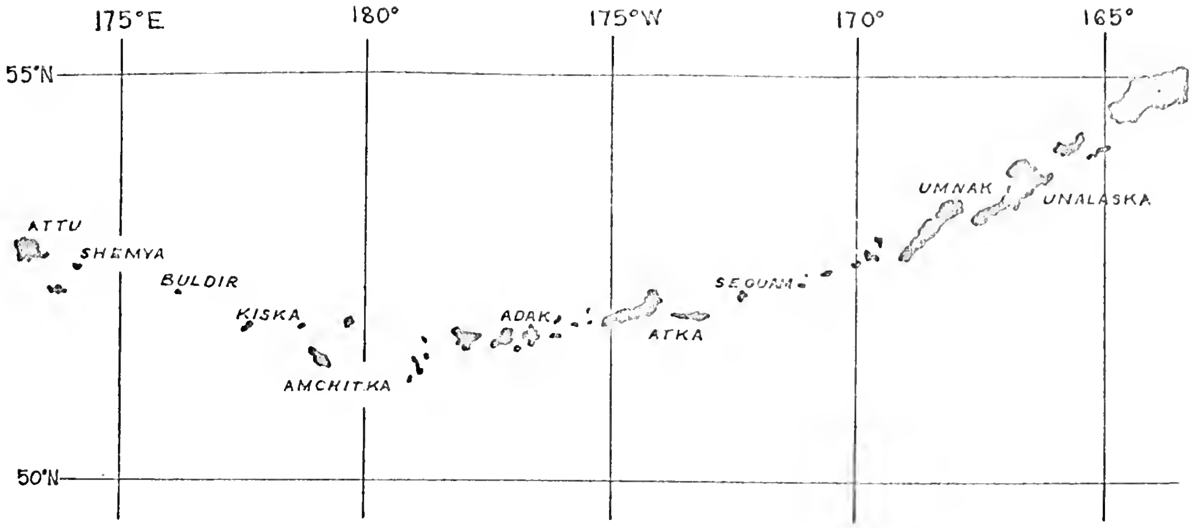


Figure 2. The Aleutian Islands

The Aleutian chain includes 14 large and about 55 small islands in addition to innumerable rocks and islets lying between latitudes 51° and 55° north. Three of the islands, all at the eastern end are larger than 500 square miles in area. The largest island is Unimak which also has the largest mountain, Mount Shishaldin, an active volcano rising to a height of 9,387 feet. Most of the islands, particularly the large ones, are rugged and mountainous. The shore lines are irregular and deeply indented with towering rocky cliffs rising abruptly from the sea. Some of the smaller islands and one large island, Amchitka, are more regular in outline, with low and relatively flat surfaces (Collins et al., 1945).

Continental glaciation did not extend over the Aleutians; however, individual ice caps formed on the larger mountains. The rugged mountain areas, unrelated to constructional volcanic landforms, result from Pleistocene glaciation and subaerial erosion as found by Fraser and Snyder (1959) for Adak and Kagalaska Islands. Visible glacial deposits are rare, because most of the debris was dumped into the sea, and the remainder

covered with volcanic ash.

The islands are mainly of volcanic origin and contain numerous active or recently active volcanoes; they are zones of intense seismic activity. Thirty to forty active volcanoes exist, the largest being Mount Shishaldin on Umnak (Freiday 1945). Some seventeen calderas, large collapsed craters over one mile wide, have been recognized, the largest being a caldera measuring 10 x 11 miles on Umnak Island (Eardley 1962). The most recent birth of an island by volcanism in the Aleutians is that of Bogoslof, "The Voice of God," which first emerged some 22 miles north of Umnak in 1796. Since the first violent eruptions, continuous volcanic activity and erosion have changed the topography repeatedly and drastically. Lightening and thunder, rare in the Aleutians, but often associated with eruptions, are frequently seen in the cloud of vapor, smoke and ash rising from Bogoslof (Morgan 1947).

The southern part of Kiska and the nearby islands of Attu, Agattu, and the Semichis at the west end of the Aleutians lack the young stratovolcanoes characteristic of the central and eastern islands (Eardley 1962). The rocks have been found to become younger from southeast to northeast. The older volcanics of the arc seem to include both shield volcanoes, characterized by many relatively thin flows, with a small proportion of fragmental material, accumulated on slopes of low declivity (about 10°), and stratovolcanoes or composite cones, the slopes of which approach the angle of repose of the fragmental material (about 30°). The major active volcanoes of the arc are without exception composite cones. The age of the arc as we see it today is Cenozoic (within past 70 million years) in

age, but fossils found in the older underlying volcanics show aspects in its evolution as old as Paleozoic (at least 200 million years ago) (Eardley 1962).

Basic bedrock units are andesitic to basaltic in composition. These rock types may occur in layers of lava flow, breccia, cinders, tuff and ash of varying gradation. Commonly an ash mantle of recent origin covers the islands. On Adak this mantle is as much as 7-1/2 feet thick and grain size varies from coarse to fine (Crandall 1963, Coats 1956). In addition to these basic materials, granites, diorites, and other acidic rocks have intruded into the older formations. Eardley (1962) believes that these continental types can be attributed to fractional crystallization because of the difficulty of explaining a continental origin. Sandstones and shales of Tertiary origin occur sporadically in the Aleutians (Collins _et al._, 1945).

The Mariana Islands

The Mariana Islands form a chain extending in a north-south direction for a distance of about 600 miles along the western edge of the Pacific Basin. Lying between latitude 13°26' to 20°33' North and longitude 144°39' and 146°05' East are fourteen single islands and one group of three small islands as shown on Figure 3. The total land area of this mountainous island arc is about 393 square miles with over half that area made up by the largest and southernmost island, Guam (Britannica 1964).

The islands are the exposed crests of mountains on the eastern

border of the long arcuate submarine ridges separating the basins of the Philippine Sea and the Pacific Ocean. The foredeep of the Mariana island arc contains the deepest depth yet measured, 35,800 feet in the Nero Deep southeast of Guam. The Mariana Ridge appears to have two longitudinal crests which are concentric and strongly convex to the east. Like most mountain crests, both are discontinuous and irregular. The southern Mariana Islands lie on the eastern crest; the northern Mariana Islands on the western crest (Corwin et al., 1957).

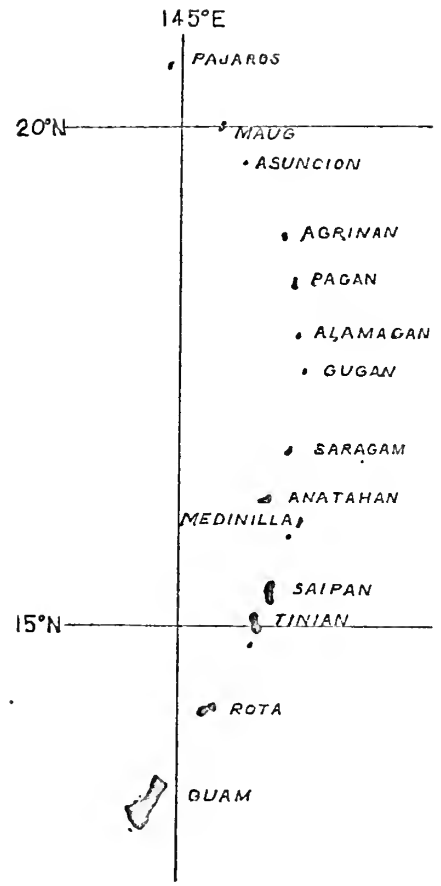


Figure 3. The Mariana Islands

The northern Marianas are small islands compared to the southern group, but they are generally higher and have much more rugged relief. The maximum elevation of the Marianas is 3,136 feet in the northern group while the maximum elevation of the southern islands is 1,5[illegible]0 feet on Saipan.

The major geologic characteristic of the northern islands is the volcanic activity occurring there today and in Recent times; the southern islands have been long silent. The volcanoes of the northern islands, such as Pagan, retain much of their original form and structure. As much as three-fourths of the land surface of Pagan consists of barren lava fields and pyroclastic debris. A radial drainage pattern has developed

from the flood flows of torrential rains; most rainfall produces little surface runoff on the unweathered volcanics. Hot springs, sulfur deposits and steam vents are frequent, and volcanic phenomena in the form of fire fountains, ash falls and fluid basalt flows have occurred within this century on Pagan (Corwin et al., 1957).

The southern islands commonly are veneered with limestone deposits even on the highest peaks. Deep lateritic weathering, uplifted reef limestones and wide fringing reefs typify the southern islands such as Guam and Saipan. Terracing from higher sea levels on the greatly eroded and faulted hills is common. The limestone deposits are many hundreds of feet thick in some instances indicating a long continuous subsidence after volcanism ceased. Both steep cliffs and drowned valleys are to be found along the coastlines. Typically the islands of the southern Marianas show two strongly contrasting drainage types--the limestone surfaces where the rainfall quickly disappears into sinks and crevices without any surface drainage, and the volcanic surfaces with well-developed surface drainage features, including permanent streams.

Solution is obvious as a dominant geomorphic process in the limestone regions. The degree of solution is indicated by the existence of a rampart formation that borders the outer edge of limestone plateaus or terraces. On Saipan these features stand from six to ten feet above the general terrace level and form a natural rampart. On Tinian, behind the ramparts are solution pinnacles, the remnants of the original strata (Cole and Bridge 1953). Probably the rampart develops and persists on a limestone surface edge because the solution opportunity is greater on

the inner, and usually slightly lower, surface; the rainwater drains inward and downward rather than over the cliff. Furthermore exposure of coral limestone to air as in a cliffline results in its hardening and becoming more resistant to erosion, while the acid conditions of the vegetated innerland fosters even greater solubility there (U.S. Army 1956).

The igneous rocks are predominantly andesitic, although the oldest rocks on Saipan are rhyolite flows, agglomerate and pumice; however, at least ten times as much andesitic lava, agglomerate and andesitic tuffs exist (Cole and Bridge 1953). On Guam consolidated outpourings of dark andesitic lava, lithified dust, ash and blocks occur. The bulk of the pyroclastically-derived materials was water-laid. Many of the lavas display a pillow structure indicating that they too commonly came to rest below water, or were the products of submarine eruption (Cloud 1951).

It is believed that volcanism in the southern islands ceased early in the Miocene epoch (approximately 11-26 million years ago) or possibly before. Subsequently major structural features were produced by normal faulting, the latest movements occurring in late Pleistocene or even Recent epochs. The structure of the southern islands is quite complex as compared with the more simple and better exposed volcanics of the northern islands.

The Truk Islands

The Truk Islands constitute what is called a near-atoll at latitude 7°21' North and longitude 151°40' East as shown on Figure 4. The group

contains twelve volcanic islands and 64 coral islands, 41 of the coral islands lying on the barrier reef surrounding the central islands.

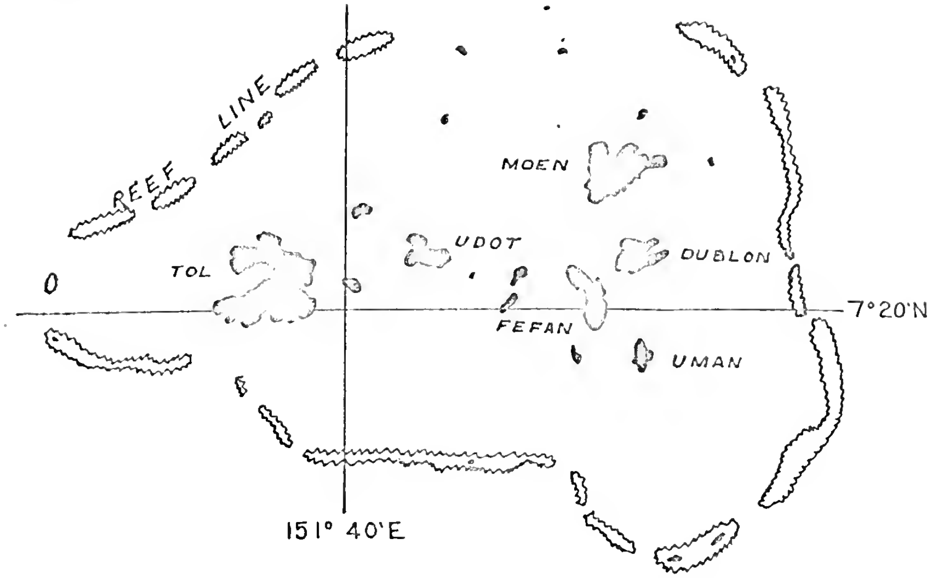


Figure 4. The Truk Islands

The barrier reef, some 125 miles long. is roughly triangular in shape and shows as emergent features the 41 low-lying coral islands. The largest coral island is one-quarter mile wide and two miles long. The highest altitudes of the coral islands are from five to eight feet (Stark and Hay 1963). The whole of the reef island area is only 1.6 square miles (Piper [illegible]). The barrier reef probably originated as a fringing reef around the original volcanic island mass. As the once single large island sank the coral grew upward now marking roughly the original shoreline.

The inner volcanic islands are remnants of a large shield volcano, now inactive, greatly dissected by faulting and subaerial erosion, and partly submerged. Sinking of 1000 to 2000 feet is indicated to account for the individual islands.

In the Truk Islands lava flows predominate, but pyroclastic material

is interbedded with flows. No remains of the original crater walls now exist. Most lava apparently issued from fractures that now contain dikes. Lava flows and dikes consist of olivine-rich basalt, melitite nepheline and nepheline basalts, nepheline basanite, andesite, trachyte, and gabbro. These lavas represent the alkalic-olivine-basalt-trachyte association common in the Pacific Basin east of the andesite line.

The largest of the volcanic islands is Tol, with an area of 13.2 square miles. Tol is formed by four upland fault blocks separated by deep embayments, and is geologically different from the other inter-lagoon islands. Tol contains the highest point of land in the lagoon with Mount Tumuital rising to 1,453 feet. Tol consists almost entirely of olivine basalt and andesite flows that are cut by steeply dipping fractures and dikes. The flows are thinner and more vesicular than the other islands, ranging in thickness from 2 to 60 feet (Stark and Hay 1963).

Moen, the second largest island with an area of 7.2 square miles, is a mountainous mass of lava and indurated pyroclastic rocks, bordered generally by unconsolidated marsh sediments, beach deposits, and mangrove swamp detritus. The flows are gently dipping columnar-jointed basalts 35 to 100 feet in thickness. Trachytic, andesitic, and basaltic debris is found in lava beds as well as independent flows of andesite and trachyte. Volcanic sedimentary deposits are widespread on Moen grading from breccia to water-rounded conglomerate. Faulting, dikes and vents have not been found on Moen (Stark and Hay 1963).

The drainage pattern on all the high Truk Islands except Tol, is dendritic; on Tol it is dendritic and rectangular. Most streams drain in

deep ravines, but large valleys also occur. The largest valley is on Moen and is about a mile long, one-third of a mile wide and 500 feet deep. Typical of valleys in basalt flow terrain, the valley walls are concave and the valley deep with a gentle gradient.

The Hawaiian Islands

The Hawaiian, or Sandwich Islands, are a chain of islands near the center of the North Pacific Ocean, some 1578 miles in length trending east southeast-west northwest between latitudes 18°55' and 28°25' North, and longitudes 154°48' and 178°25' West as detailed on Figure 5.

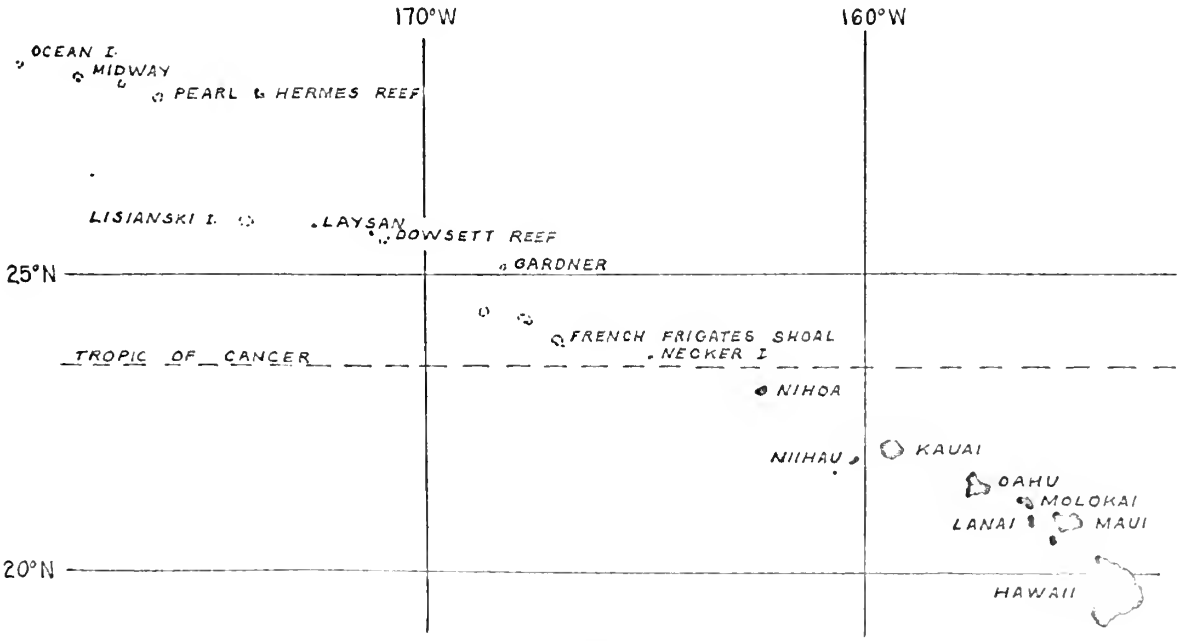


Figure 5. The Hawaiian Islands

The Hawaiian Island group consisting of both volcanic and coral islands built up from depths of 15,000 to 18,000 feet, is the northern part of the Central Pacific island groups. It has the highest elevation of any oceanic island with Mauna Kea rising to 13,784 feet. The islands are

believed to have been formed during the Tertiary (within the past 70 million years) with volcanic activity progressing southeastward. Only the easternmost and largest island of Hawaii now has active volcanoes. Hawaii may have been initially formed as late as the Pliocene (within the past 11 million years). Submarine contouring indicates that a downbowing, the Hawaiian Deep, exists around the ridge on which the islands rise. This may be due to the heavy loading of the earth's submarine crust by the volcanic piles (Eardley 1962).

The chain of islands may be divided into three segments according to the type of island found in each. The southeast segment consists of the familiar high volcanic islands, none less than 1300 feet in elevation. The northwest segment, except for Gardner Island, has no volcanic rocks exposed, and consists of coral reefs and sand islands. The middle segment is a link between the two extremes of high volcanic islands and low coral islets, having relatively small greatly eroded volcanic islands on greater submarine banks. These submarine banks exist continually in conjunction with the older islands at a depth of about 300 feet below present sea level; a narrower shelf at 60 feet below sea level also occurs according to Stearns (1947). It seems reasonable to accept the opinion that the westerly islands were also once high volcanic islands like the present islands of the southeastern segment, but that they have been truncated by stream, wind, and wave erosion.

In the northwest segment of the Hawaiian Islands, Pearl and Hermes Reef is perhaps typical.- It owes its name to two English whalers who were wrecked there in 1822. The reef is an atoll of irregular oval shape about 17 miles by 10 miles in dimension. In the lagoon are four islands

covered with scanty vegetation and a number of low and barren islets. The islands consist of sand and shift in size and shape easily. One of the largest islands is Southeast Island about a mile long and less than a quarter of a mile wide. Elevated worn limestone rock, surviving portions of an ancient reef, stand at about four feet above high tide (Galtsoff 1933).

Nihoa (Bird Island) is the largest island of the central old volcanic islands. It has an area of about 1/4 square mile and a maximum height of 895 feet. From a distance Nihoa resembles a great rock tooth. Inaccessible cliffs surround it on all sides except the south where the ground slopes down to a small bay. The rock apparently represents a portion of the southwest quadrant of the original cone. This remaining portion lies near the southwest end of a submarine bank some 120-240 feet in depth. It appears that the original cone was truncated by the sea and winds more strongly from the northeast, the direction of the prevailing northeast tradewind (Palmer 1927). According to Davis (1924) the Hawaiian Islands lie in the marginal belt of the coral seas; they would be expected to have banks truncated by lowered stands of the sea during the Pleistocene, but very likely may not have developed favorable conditions rapidly enough for coral reef growth before submergence.

On Nihoa no permanent streams occur, but numerous V-shaped valleys exist. A wave-cut terrace from four to eight feet above sea level extends along the south coast. Caves are found at the cliff base.

The rocks of Nihoa are principally olivine basalts in both flows and intersecting dikes. Magnetite is found in appreciable quantities.

Some conglomerate weakly cemented by earth and bird guano is exposed (Palmer 1927).

The geology of each of the large high islands in the easternmost end of the chain is covered in a very comprehensive manner by a series of bulletins of the Hawaiian Division of Hydrography. The following summary of information on Maui, the beautiful "Valley Isle," is from one of these excellent bulletins by Stearns and MacDonald (1942).

Maui is the second largest of the Hawaiian group, being 48 miles long and 26 miles wide at its widest point, with an area of 728 square miles. The island is formed of two volcanoes, East Maui being 10,025 feet high and West Maui, an older deeply-dissected volcano, being 5,788 feet in elevation. The flat isthmus which connects the two volcanoes was made by lavas from East Maui banking against the West Maui mountains. The basic island profile is that of two broad shield-shaped domes of thin-bedded lava flows dipping away from the two respective summit vents. Numerous, spectacular green-mantled canyons cut the mountain sides.

The oldest rocks exposed on East Maui are very permeable primitive basalts which were extruded probably in Pliocene and early Pleistocene times from three rift zones. The later Pleistocene lavas are andesites, andesitic basalts, and picritic basalts. These contain interbedded soils, thin vitric tuff beds, and lava filled valleys. On West Maui the oldest rocks are very primitive basalts which flowed in Pliocene and early Pleistocene times from two main rifts and many radial fissures; soda trachyte and oligoclase andesites partially overlie the dome.

Sedimentary rocks on Maui are chiefly of late Quaternary age and consist of alluvial fans, landslide debris, delta deposits, and valley

fills of poorly permeable and poorly assorted bouldery alluvium. Mud flows are also found. The isthmus contains calcareous sand dunes of three ages.

An unusual phenomenon is found on the Eke, of Maui, a flat, swampy plateau of trachyte lying 4,500 feet above sea level. These uplands are covered with an acid peat bog; bedrock of the bulbous trachyte dome is occasionally exposed. Shallow water pond depressions some 5 to 20 feet across, and aligned along cracks, are found in the rock surface. It is hypothesized by Stearns (1942) that these depressions are due to a very unusual solution reaction of the trachyte by the constantly present rain-water.

In the Hawaiian Islands theater - headed valleys are an impressive geomorphic feature. These valleys, forming in very pervious basalts, develop extraordinarily deep canyons which widen at their heads, ending abruptly in great cirque-like amphitheaters. The island of Tahiti in the Society Islands is especially famous for these theater-headed canyons. Williams (1933) in describing these impressive valleys on Tahiti says that, "There can be no doubt that these curious features owe their origin to the undermining and collapse of massive lavas resting on softer beds of decomposed lava or ash." At many places Williams observed clear evidence of sapping action by underground water. At the base of some of the cliff walls in the valley heads are enormous landslide blocks beneath recent scars in the cliff above. Even insignificant tributaries may develop such an impressive valley.

The Bermuda Islands

The Bermudas consist of over 150 islands and islets grouped together in a great hook trending northeast-southeast at latitude 32°17' North and longitude 64°46' West as shown on Figure 6.

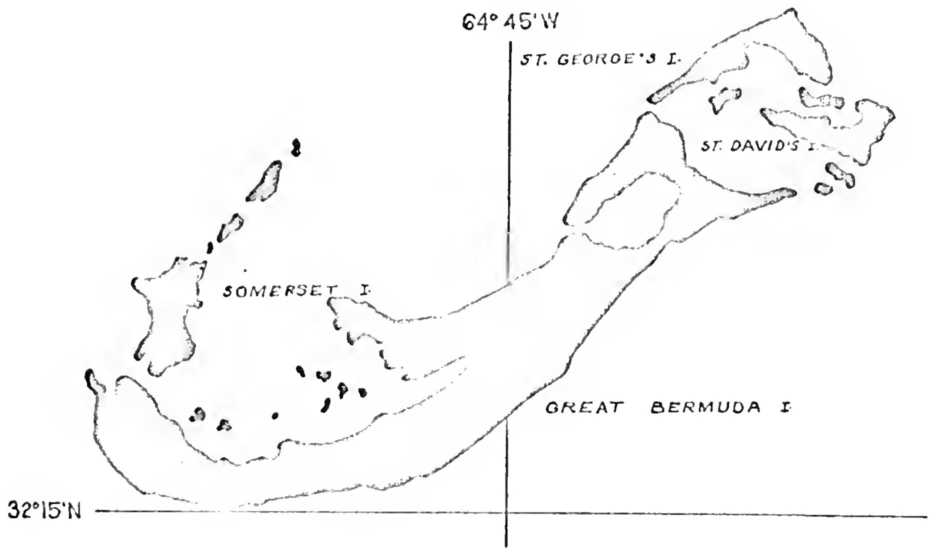


Figure 6. The Bermuda Islands

The Bermudas, or Somers Islands, with a total land area of 20 square miles, are the northernmost coral islands in the world. They mark an extreme northerly loop of the marginal belt of the Atlantic coral seas due to the warming effect of the Gulf Stream.

The islands are perched on the southeast side of an elliptical submarine platform about 22-1/2 miles by 10-1/2 miles with a total area of 200 square miles, which rises some 15,000 feet from the ocean floor. The present top of the platform lies 60 to 70 feet below sea level. A coral reef, mostly submerged, grows from one to three miles inside and along the outer margin of the platform. Within the lagoon the depth of

water is generally 60 feet or less. The appearance of the Bermudas is that of an atoll, but in fact the corals and associated forms constitute only a thin veneer (Sayles 1932). The islands rest on a basaltic lava foundation. The main outer slopes of the bank are 12° reaching a maximum at one point of 23°. This is indicative of a cone built chiefly of basaltic lava flows rather than felsic breccias and tuffs (Schuchert 1935).

The first deep borings in the islands in 1912 showed that deeply weathered volcanics rest at 245 feet below sea level and are overlain by some 380 feet of aeolian limestone. At 560 feet below sea level solid bedrock of basaltic lava occurs (Sayles 1932).

The topography of Bermuda is characterized by the forms of consolidated wind-blown dunes of calcareous shell sands made in Pleistocene time. In this respect the appearance is quite similar to the Bahamas; however, whereas the Bermudas' deposits are of wind-blown shell sands, the Bahamas' dunes are of calcium carbonate sand grains originating as inorganically precipitated oölites. The dunes have a gentle slope from the south shore and steeper slopes to the north with depressions between. The more gently rolling areas are regions of older dune formations; this is flanked north and south by younger dunes. The crossbedding slopes indicate the dunes were moving inland toward each other. This movement is not necessarily a function of the prevailing wind, but of the source of the supply of sand (Sayles 1932). The hills are generally less than 150 feet above the sea, but several are over 200 feet, the highest being 259 feet. ... is no apparent karst topography; most of the swamps and marsh areas

seem to be original low places never covered by the more recent dunes. The indurated aeolianite is extremely porous; even the hardest rains produce little surface runoff. During the Pleistocene, however, surface streams are thought to have been present because of ancient eroded channels that go out to the sea. Some of the interdune depressions are filled with either marine or fresh water muck and peat to a depth of at least 52 feet (Schuchert 1935).

The top 15 feet of the fragmented shell limestone is relatively compact, but then poorly-cemented sands are encountered; these harden upon exposure to air. The houses of Bermuda, including the roofs, are traditionally made of this soft limestone which cuts easily to shape, but hardens into a permanent construction material.

At least four different strata of red-brown soils are interbedded in the dunes; usually they are only a few inches thick, but some pockets are as thick as 12 feet. These soils apparently formed during periods when rainfall was great and vegetation flourished. Some of the soil layers represent formation times of as much as 200,000 years. It takes from 60,000 to 120,000 years of time and from 100 to 200 feet of aeolianite to produce one foot of soil (Sayles 1931).

Many different stands of the sea level are evidenced by solution cavern formations at different levels and marine benches above present sea level. Sea caves with abundant stalactites and stalagmites are found as much as 60 feet below and 25 feet above sea level. Marine benches are seen between 6 and 12 feet above sea level with one at 25 feet elevation.

The volcanics could have occurred at any period of time of marked instability, but probably during late Cretaceous time (about 70 million

years ago). By the end of the Tertiary (about 1 million years ago), the mountainous islands had been reduced to submarine platforms. In the shallow waters marine oölitic limestone formed, much as it does today on the Bahama Banks, in addition to forminiferal (coral) marl. Then alternate submergence and emergence (of about 10 times as much land area as is exposed today) allowed a heavy deposit of shells to form and become the thick formations of aeolianite which now make up the islands.

OCEANIC ISLAND CLIMATES

Climate may best be considered as the prevailing weather characteristics of an area over a long period, considered both in average magnitudes and variability of the elements of weather. Weather by comparison is the atmospheric condition existing at any given time (Trewartha 1954). Thus to give a satisfactory climatic picture of the oceanic islands this section will describe first in general the elements of wind and air pressure, temperature, atmospheric moisture, and precipitation, as related to oceanic or marine regions, and then secondly the variability of these elements in time and local climate.

Climatic Controls

For the oceanic island four principal terrestrial factors, or climatic controls, govern the climate. A working knowledge of how these controls function can enable reasonable estimates to be made of the general climate of most oceanic islands even if specific data is unavailable (Halpine and Taylor 1956). The climatic controls which must be considered are:

1. the latitude,
2. the land and water distribution,
3. ocean currents,
4. topography.

Latitude influence is manifested in the obliquity and duration of solar radiation. This in turn determines the amount of insolation available

to heat the land or ocean surfaces and the air. The minimum obliquity of the sun's rays may vary from 0° for islands within the tropics where the sun stands directly overhead to about 28° for the Aleutian Islands; at the poles the minimum obliquity is 66-1/2°. The result is that the sun's rays which do touch the cold northern latitudes even in the long summer days provide far less heat than is possible in the tropics. The length of day varies from a 12 hour day throughout the year in the Galapagos Islands on the equator to a 17 hour day in summer and a 7 hour day in the winter for the Aleutians. Accordingly, equatorial regions are fairly constantly warm, while far northern or far southern latitudes have temperature extremes of summer and winter, but being colder on the average for the entire year.

The principal influence of the deep ocean water is to moderate temperatures. Because of the high specific heat of water and water's transparency to the sun's rays, the ocean warms and cools much more slowly than an opaque land surface. The heat is not concentrated at the surface of the ocean as it is on land; instead a great depth of water is heated through light-wave penetration and turbulent mixing. Hence both diurnal and seasonal temperature variations in the air over water are relatively small compared to that over land. In typical oceanic climates the diurnal range of the surface water temperature is generally less than 1°F; the annual range is below 20°F. Exceptions exist only in the polar oceanic regions where ice produces the same effects as a land surface (Britannica 1964).

Surface ocean currents generally move in the same direction as the

winds which have caused them; however, it is the temperature of the ocean which, to a large extent, determines the air temperature on the small oceanic island. Thus the Galapagos Islands lying on the equator, but in the path of the cold (63°F) Peruvian current may have a sea level air temperature of 70°F, while the Gilbert Islands, also on the equator, but at the far end of the warm equatorial currents, has a temperature of 89°F. Major temperature contrasts between cold ocean currents and warm air, as exists in the Aleutians in the summer, may produce thick persistent fog as the warmer air is cooled.

Topographic features, such as the mountainous island, may greatly modify the general climate to be expected in a region. The most obvious, and hydrologically important, effect is to block the normal wind pattern; topographic highs force the wind to deflect or ascend. When the moist oceanic air is forced to ascend into the colder elevations precipitation usually occurs. Consequently most high islands experience much greater rainfall than low islands in the same region. The effect of elevation on temperature is similar to an increase in latitude; with each 1000 feet of elevation the temperature will decrease from 3 to 5°F. Finally it should be recognized that certain slopes of a mountain will be bathed in constant sunlight while others will be masked in deep shade creating great dissimilarities of climate.

Less obvious, but important, secondary controls affecting local climate are vegetation and human activity. These controls may in fact be dominant in the microclimate regime, the first few feet of space above the surface of the ground. As examples, under a canopy of trees, temperature

maxima are low and minima higher than over an open surface at the same latitude; also humidity is generally much higher in the vicinity of a vegetated area than in a barren region. Modern cities produce a climate all their own, and they usually average warmer temperatures, lesser humidity, and greater precipitation than the surrounding countryside.

General Planetary Circulation

Winds are caused primarily by the differences in heating of the earth's surface; the heating variation creates pressure differentials which impel the movement of large air masses. About half the earth's surface (roughly the region between 30° North and 30° South latitude) has a large net gain of solar heat each day; the remainder of the earth pole-ward, has a net loss. The general circulation of the earth acts to re-distribute the heat over the earth's surface.

As illustrated on Figure 7, the general circulation is basically characterized by alternating belts of low and high pressure.

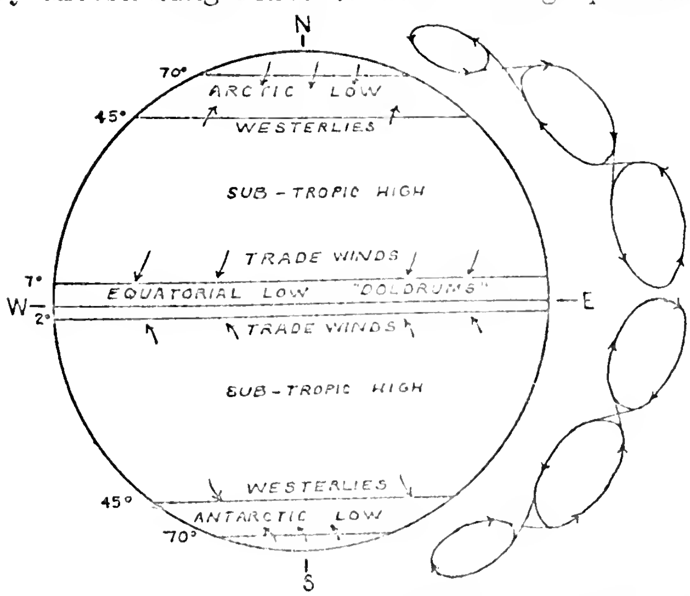


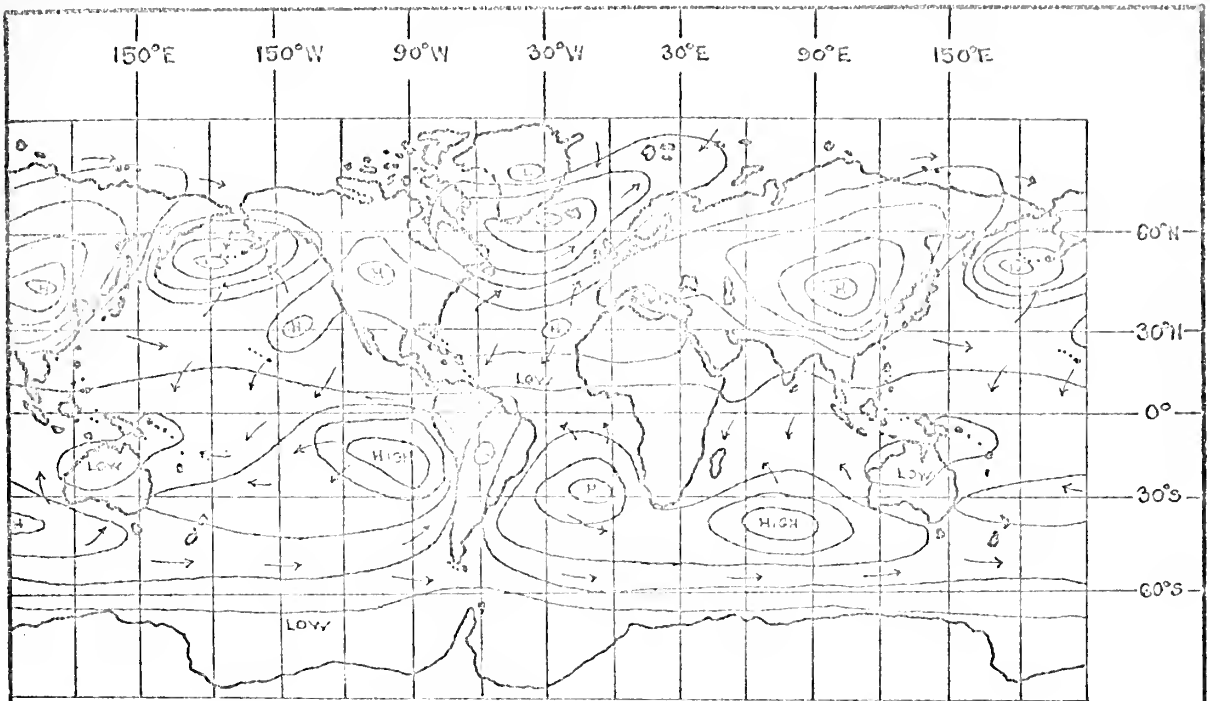
Figure 7. General Planetary Circulation

Surface air from both subtropical high pressure belts flows toward the equatorial low. This movement of air, deflected by the Coriolis force, constitutes the steady easterly trade winds over the oceans. Poleward from the semipermanent high-pressure systems at about 25° latitude North and South the westerly winds move toward the Arctic and Antarctic lows.

Significant regions of relative calm or variable winds prevail at the middle of the belts of both low and high pressures. Near the equator in the region known as the doldrums the winds slacken into fitful breezes coming first from one direction, then from another. On the outer margin of the trade winds, corresponding roughly to the middle of the subtropic high belt, are regions of calm descending air, the so-called horse latitudes.

The foregoing simple planetary circulation described is modified to a great extent by the influence of the large continental landmasses. The continents act not only as topographic barriers, but generate seasonal high and low pressure centers which interact with the maritime pressure centers. Continents in winter cool off faster than the ocean causing great high pressure centers; in the summer lows are formed over large landmasses. Plate V shows the circulation of winds over the oceans as established for the pressure center patterns for January and for July (Bartholomew 1956).

In the Pacific on both sides of the equator, to a latitude of about 20°, easterly trade winds blow. The region of doldrums consist of a wedge-shaped area with the base resting on the West Coast of the Americas. In the western central part of the Pacific the huge landmass of Asia causes the trade winds to be replaced by the seasonal monsoon winds. The boundary



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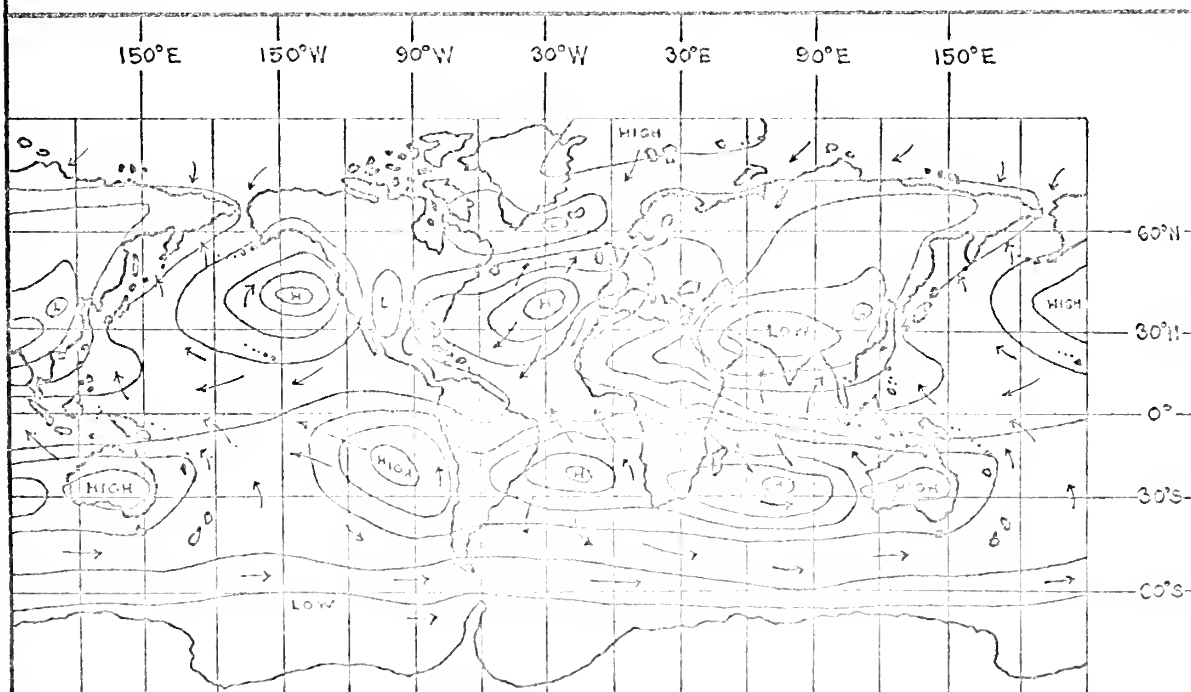

JULY

PLATE V WORLD PRESSURE CENTERS

INFORMATION FROM BARTHOLOMEW (1950)

of the monsoon region is about 5° North to 15° South, and 160° East to 175° West. The North Pacific on the Asian side from the tropics to the Bering Sea has a monsoonal reversal of prevailing winds, winter and summer. In winter this is a very cold, dry, northwesterly wind; in summer a warm, moist, southeast wind. On the American side of the North Pacific from Southern Alaska to Northern California marine air continuously moves toward land or follows coastal mountain ranges except for temporary modification when strong continental highs develop. In winter the North Pacific winds are southerly; in summer they shift clockwise to become northerly (Britannica 1964).

The major climatological features of the North Atlantic are the "Azores high" and the "Iceland low," both fairly permanent features. In the Northern Hemisphere the winds blow clockwise around the high pressure region and counterclockwise around the low. The prevailing winds on the equatorial side of the Azores high are northeasterly to easterly. This circulation causes the trade winds to blow stronger. Between the Azores high and the Iceland low, westerly winds prevail, being strongest in winter (Britannica 1964).

In the South Atlantic a high pressure area corresponding to the Azores high occurs between 20° to 30° South. On the equatorial side of this high the southeast trade winds blow weakly in summer and strongly in winter. Between the north and south trade wind belts, in a wedge shape with the base on Africa, lies the equatorial calm, the doldrums, characterized by light wind and heavy downpours. A belt of low pressure surrounds Antarctica. Between this and the high at about 20° to 30° South, westerly

winds prevail, being particularly strong between 35° to 45° South, famous as the Roaring Forties (Britannica 1964).

The Indian Ocean climate northward from 10° South is predominantly influenced by the monsoon winds. From October to April northeast winds prevail in the north latitudes and northwest winds in the south latitudes. From May to September, south and west winds prevail throughout the Indian Ocean. The northerly winds are predominantly dry, while the southwesterly winds are moisture laden and bring torrential rain to the whole of India. Southward of the Seychelles-Chagos-Cocos Islands (4° to 12° South) the southeast trade winds prevail. South of 30° South westerly winds occur which are particularly strong between 40° and 55° South (Britannica 1964).

In quiet air regions and on larger landmasses diurnal, or daily, monsoons may be induced by the ocean-land contrasts in marine regions. During the day the rapid and strong heating of the landmass creates a much higher surface termperature than the water surface temperature. The warmer air over the land moves upward, and a flow of air from the water moves in to take its place. A daytime sea breeze is thus generated. Velocities of this breeze show great variation from not greater than 8 mph (miles per hour) in the middle latitudes to 25 mph on dry regions surrounded by cold water. Clear skies favor large ocean-land temperature contrasts and stronger breezes. The sea breeze may result in air temperatures as much as 20°F cooler on the coast as compared to an inland position. The maximum velocity occurs at about 1:00 to 2:00 P.M.

At night the temperature contrast is reversed with the ocean retaining its warmth while the land becomes cool through radiation. Thus at

night cool air flows seaward as a land breeze to replace the rising warmer sea air (Trewartha 1954).

Oceanic Temperatures

On small oceanic islands the temperature of the water is the major determinant of the general temperature of the island. Because of a tendency for an ocean-land breeze to develop, the periphery of an island may be many degrees cooler during the day than the interior; at night the air of the land breeze from a mountainous interior may be cooler than the ocean temperature.

Small temperature changes, both diurnal and seasonal, distinguish oceanic islands from continental environments. The surface of the ocean maintains a diurnal range usually within 1°F. The air near the water also changes little; this effect prevails for about 900 feet upward. Above this level the temperature variation is controlled by radiation only and the range of temperature may be considerably greater. Accordingly on the high islands, and in particular larger islands, it cannot be assumed that diurnal temperature variation is necessarily small. At most low level oceanic island stations the range of recorded daily maximum-minimum temperature is about 10°F.

The range of temperatures on a landmass at any one time depends almost entirely on elevation, the temperature decreasing from 3 to 5°F for each 1000 feet of elevation. While in Hawaii the average daily sea level temperature remains between 71 to 79°F throughout the year, temperatures below freezing and summer snow may be found on the higher levels

of Mauna Kea (13,825 feet) and Mauna Loa (13,675 feet) (Hinds 1943).

Seasonal variation of temperature on oceanic islands is also relatively small, but is usually greatest in the higher latitudes. Even in the Aleutians (latitude 52° North) the annual range of mean monthly temperature is only 20°F. In oceanic climates there is commonly a time lag of the thermal extremes behind the solstices (June 21 and December 21). In the ocean of the Northern Hemisphere August is often the warmest month (Britannica 1964). The annual temperature variation of several representative small oceanic islands is given below (Air Ministry 1958):

Pitcairn Island 25° 04' S 130° 04' W 240 ft.

	J	F	M	A	M	J	J	A	S	O	N	D
ave. daily min.	71	74	72	69	68	76	64	64	64	65	67	70
" " max.	82	83	83	79	77	74	72	72	73	75	78	80

Canton Island 2° 46' S 171° 43' W 12 ft.

	J	F	M	A	M	J	J	A	S	O	N	D
ave. daily min.	79	79	78	78	78	79	79	78	79	78	78	79
" " max.	90	89	90	90	91	91	91	91	91	90	90	90

Yap Island 9° 30' N 1[illegible]° 0[illegible]' E 96 ft.

	J	F	M	A	M	J	J	A	S	O	N	D
ave. daily min.	75	75	75	77	77	76	75	75	75	76	76	76
" " max.	86	86	87	85	88	88	85	88	88	88	87	86

Isotherms for the air over oceans in January and in July are presented on Plate VI. Temperature inversions frequently occur in the northern oceans around the Aleutians in the Pacific and the southern coast of Newfoundland in the Atlantic. In the southern oceans inversions are found off the South American coast in the Galapagos Islands and along the west central

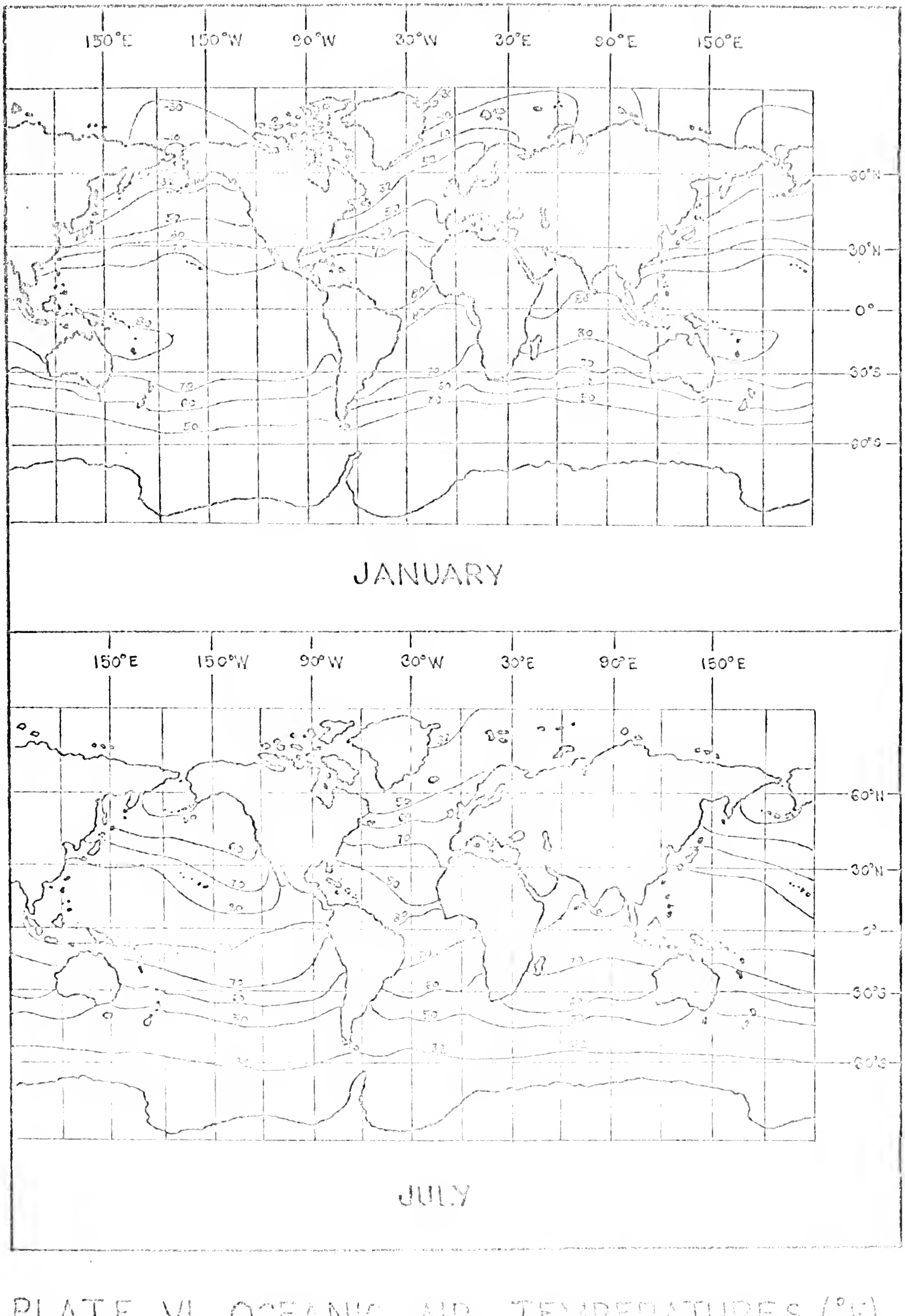

PLATE VI OCEANIC AIR TEMPERATURES (°F)

INFORMATION FROM BARTHOLOMEW (1950)

coast of Africa. In these cases the inversions are caused by warm air overlying cold ocean water.

Atmospheric Moisture

Among the unique climatic characteristics of oceanic regions is high humidity. The zonal distribution of relative humidity varies from being greatest at 60° and 0° latitudes, averaging about 83%, to the lowest at 30° latitude, averaging about 73% (Trewartha 1954). As an exception however, Malden in the Line Islands at 4°03' South has a very low relative humidity for a tropical island averaging 58% in the afternoon (Wiens 1962). Normal annual variation appears to be in the order of 4 to 6%. Diurnal variation ranges from 2 to 15% being greatest at early morning slightly before sunrise and lowest in early afternoon.

Fog, while not common, may be of major climatic significance in certain island groups, namely the Aleutians and the Galapagos. In both cases the fog blankets which form are advection types, caused by warm moist marine air moving over cold ocean water. In the Aleutians the fog is created as subtropic air moving north is changed from 70°F to about 50°F by the cold Arctic currents moving south from the Bering Sea. Neither sun nor strong wind can dissipate the fog (U.S. Air Force 1950). While fog may be readily coalesced by vegetation it is not likely to develop into rain.

Atmospheric moisture may be deposited as dew on clear nights on some islands. In most oceanic situations a drop of 10°F should be sufficient to cause dew formation. Probably only on dry islands of meager

rainfall such as Lanai, which gets only 10 inches annually along the coast, is dew noteworthy. On Lanai, however, deposition of dew is copious enough that the early natives collected it for drinking water by shaking it from shrubbery and spreading out oiled cloths on which it would collect at night (Emory 1924).

Precipitation on Oceanic Islands

Certainly the most significant climatic element from a hydrological viewpoint is precipitation. It logically is first considered in evaluating the possibility of finding fresh water on the isolated island. A consideration of precipitation on an oceanic island should include evaluation of magnitude, character, areal distribution as related to topography, pattern in time, and reliability.

On a very general basis it can be said that regions of low pressure have the greatest rainfall, while regions of high pressures are the driest. This is a reasonable generalization since the flow of air moving into the low pressure region ascends within the center, being cooled and precipitating rain as it does so; conversely the descending air in a high pressure region become drier. A comparison of the pressure centers of Plate V with the annual rainfall pattern shown on Plate VII, particularly in the regions of persistent lows or highs, shows this to be true. For low islands some comparative conclusions can thus be deduced; for high islands, however, the topography may be the principal precipitation determinant.

Considering near sea level stations only the heaviest [illegible]

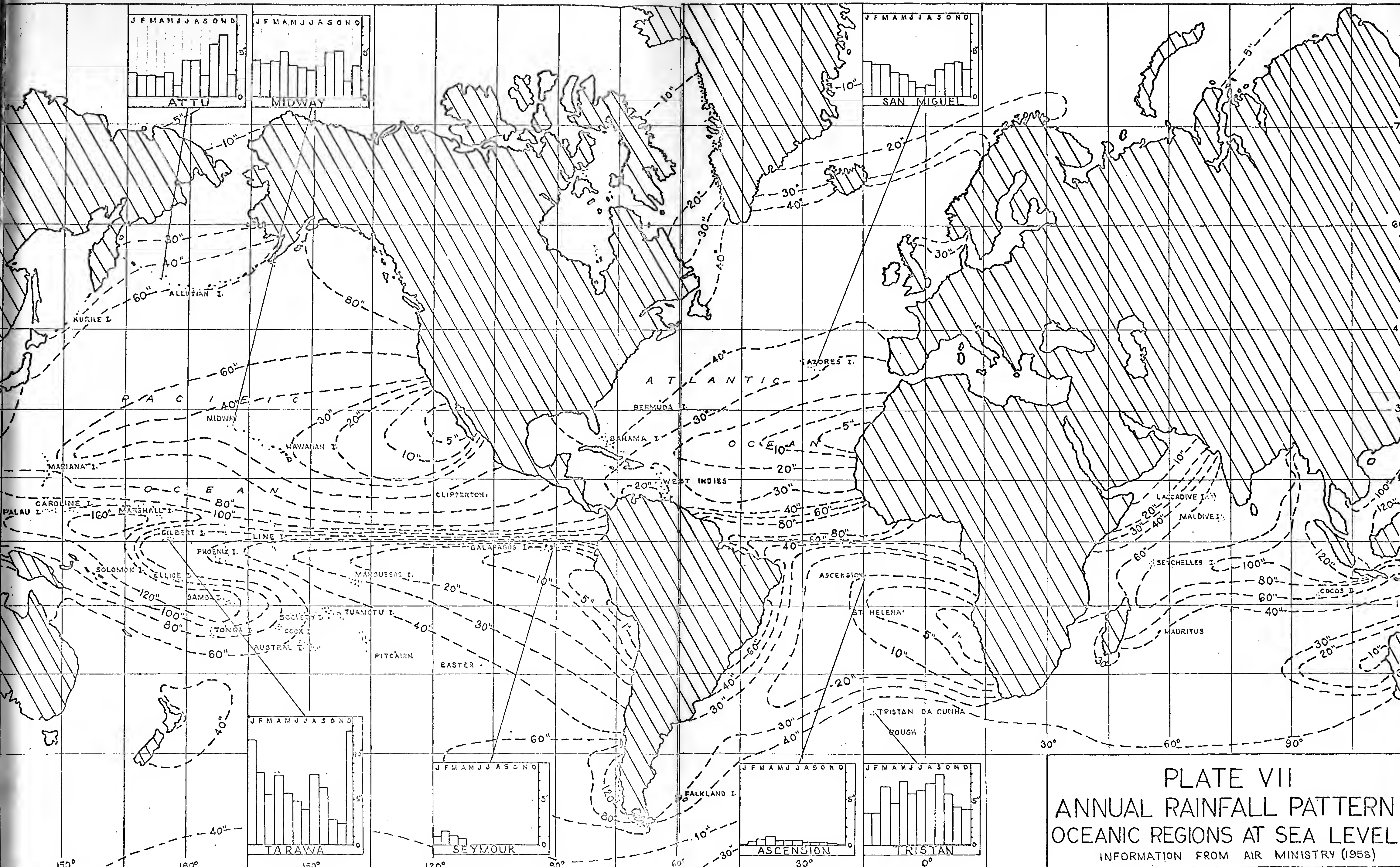

PLATE VII
ANNUAL RAINFALL PATTERN
OCEANIC REGIONS AT SEA LEVEL
INFORMATION FROM AIR MINISTRY (1958)

rainfall is north of the equator in the Pacific in a belt between 1°38' North and 8°30' North stretching from Palmyra Island (160° West) to Kayangel Island (134° East). Rainfall diminishes north and south of this zone, and also very markedly eastward. According to Wiens (1962) the concept of an equatorial doldrum belt characterized by heavy rains does not appear valid. Instead small (about three miles in diameter) vertical convection cells occur in conjunction with the unstable portion of huge horizontal eddies. Palmyra Island at about 8° North averages some 150 inches annual rainfall while Canton Island lying only 3° South averages 17 inches annually. Farther north, even in a continuing low pressure region such as the Aleutians, precipitation is much less than in the tropics. Essentially this is because the cold saturated air has much less capacity for holding atmospheric moisture than warm saturated air. Saturated air reduced in temperature from 100°F to 90°F will precipitate five times as much moisture as air cooled from 40°F to 30°F (Trewartha 1954).

Snow as precipitation is relatively unimportant on oceanic islands. It does occur in the high mountains of Hawaii and in the lower mountains of higher latitudes such as Tristan da Cunha (37° South) and the Aleutians (52° North). Even in the Aleutians snow rarely lasts for any length of time at sea level even though it is estimated that the annual snowfall is 60 inches (U. S. Air Force 1950).

It seems that the low landmasses, or even atoll complexes, have little if any effect on precipitation. The lagoon water of an atoll may be about 1°F warmer than the surrounding ocean, but it is doubtful that

this could be a significant influence on the weather. On the other hand experienced Polynesian navigators claim the presence of tiny atoll islands can be ascertained by the distribution of clouds. Even if the atolls can cause peculiarities of cloud formation, the effect upon precipitation over the atoll itself is hardly detectable and probably insignificant (Lavoie 1963). Precipitation on the atoll islands results from oceanic air convection and occasional cyclonic depression activity.

For the high islands the effect of topography on precipitation is impressive in many respects. The most apparent precipitation trend on the high island is that the rainfall increases with elevation. Mountains several thousands of feet high frequently have a wreath of clouds about their summits. Where winds blow steady from a single direction the year around as in the middle of the trade wind belts, a second trend in rainfall distribution becomes very significant; here the orographic precipitation is effective primarily on the windward side while the lee side of the oceanic island is quite dry.

The rainfall caused by a mountainous island may not necessarily fall on that land; it can fall either to leeward or windward of it. The almost barren rock island of Malpelo (3°59' North and 81°35' West), which allegedly has the distinction of being the first oceanic island in the Pacific sighted by Europeans, is some 900 feet high. It is reported that the altitude of Malpelo is sufficient to produce heavy showers that fall on the ocean a mile or so to leeward so that a vessel cutting across downwind may be drenched while the rock itself remains unwetted (Murphy 1945). Conversely the blocking effect of a high mountainous island may be reflected in precipitation some distance in front of the slope. This

is due to the moist air overriding a stagnant layer in front of the mountain surface (Trewartha 1954).

On all high oceanic islands in the trade wind belt exceeding about 2000 feet in elevation, cloud caps are formed as the cooled moist air is lifted. On the highest mountains with peaks above the upper limit of the trade winds, a great cloud belt generally hangs over the windward slope at between 2000 and 7000 feet. The position of the belt is controlled by the average temperature and wind strength. On warm days in the Hawaiian Islands, when lowland temperatures exceed 85°F, the clouds rise 1000 to 2000 feet above their normal position. When the wind velocity falls below about 10 mph the clouds may disappear. While the clouds exist, they produce heavy, almost continuous rain. The air descending the leeward slopes is heated at the dry adiabatic rate of about 5.5°F per 1000 feet of elevation and becomes very dry and warm. Hence the leeward side of a high mountain is commonly arid (Hinds 1943). Frequently the heavy windward rainfall may "spill over" the crests of intermediately high mountains (those between 2000 and 7000 feet) onto the upper slopes of the "dry" side.

The Hawaiian Islands lying in the heart of the northeast trade wind belt afford the finest examples anywhere of the effects and variation of orographic precipitation on oceanic islands. On Maui rainfall varies from an annual average of 13 inches on the leeward coast to 389 inches on the summit at 5,788 feet. 496 inches of rain fell on the Maui summit in 1937, while only 6 miles away a record low of 2 inches fell in 1938, the lowest ever recorded in the Hawaiian Islands (Stearns and MacDonald 1942). Lanai, while fairly high at 3,370 feet elevation, is a relatively dry

island because of its geographic location in the lee of the much higher island of Maui. This rainshadow effect diminishes the importance of the trade wind; in fact a definite sea breeze front can be found on Lanai nearly every summer day (Leopold 1948). The effect of orographic precipitation can be well illustrated by a summary of average annual precipitation values at various island locations as follows (Hinds 1943):

Island	Average Annual Precipitation		
	Windward	Summit	Leeward
Kauai	50-80"	476"	20-60"
Oahu (West)	30-40"	80"	20-30"
(East)	50-60"	200"	20-30"
Maui (West)	30-60"	350"	10-40"
(East)	80-200"	60-80"	10-80"
Lanai	10"	40-50"	-

The pattern of magnitude of monthly rainfall throughout the year on an island is as significant as the total annual amount. Very few locations have an equal distribution of rainfall throughout the year, but are rather inclined to have wet and dry periods. Generally a change from a wet to dry, or dry to wet, season is heralded by a change of prevailing wind direction. Most frequently those oceanic islands in the trade wind belt become wetter as the winds shift from the relatively dry trade winds to warmer more moist, winds of equatorial origin. Winds moving from cooler to warmer regions or from large landmasses, tend to produce dry seasons on the oceanic island; winds moving from warmer to

cooler regions on the ocean tend to produce wet seasons.

Some of the dry periods, even on islands of fairly substantial rainfall, can be considerable. In the Gilbert Islands, where the prevailing winds are the northeast trade winds, the average annual rainfall for all islands is about 70 inches. A pronounced wet season occurs during the winter months when monthly rainfall is from 2 to 4 times that of the other months. In 1925 for a period of eight months during the long dry period, no rain at all fell on 14 of the islands (Sachet 1957).

Representative annual rainfall patterns are shown as inset diagrams on Plate VII. General apparent patterns derived from data (Air Ministry 1958) are as follows:

1. The Aleutian Islands have a period of greatest rainfall during the fall months (monthly rainfall 2 times that of other months).

2. The Southern Hawaiian Islands have a maximum of rainfall during the winter months (monthly rainfall 2 to 4 times that of other months).

3. The Gilbert Islands have a pronounced wet season in the winter months (monthly rainfall 2 to 3 times that of other months).

4. The Central Line Islands have a major wet period during the spring months (monthly rainfall 3 to 4 times that of other months).

5. The Samoan Islands incur major rainfall from later fall through early spring (monthly rainfall 4 times that of other months).

6. The Lesser Antilles have a wet period from late summer to early winter (monthly rainfall 2 times that of other months).

Variability in annual rainfall is great, particularly on the low islands. Drought years occur on even the wettest atoll islands. The highest rainfall recorded on Fanning Island in the Line Island Group was 207.8" in 1905, but in 1950 there was a low of 27.8". At Malden farther

south, the highest rainfall was 95.6" in 1919, and the lowest was 4" in 1908 (Wiens 1962). Variation in annual rainfall for representative islands in the Gilbert Group may be illustrated by the following summary (Sachet 1957):

Island	Year				
	1948	1949	1950	1951	1952
Little Makin	73.5	119.8	50.3	153.4	131.4
Beru	87.5	48.3	9.8	61.4	45.4
Arorae	81.9	43.3	11.4	82.8	67.9

Annual rainfall is most variable along the western tongue of the equatorial dry zone (eastern Central Pacific) where the north-south rainfall gradient is steep. Variability is still higher in the Penrhyn-Tahiti region where dry conditions associated with a permanent South Pacific anticyclone to the east may prevail, or wetter weather may persist when the quasi-stationary trough line usually lying to the southeast from the South Cook Group moves east (Wiens 1962). Islands in moderate latitudes have a greater reliability of rainfall.

Tropical cyclones (known as typhoons in the Pacific and hurricanes in the Atlantic) are characteristic of low latitudes and probably develop only over water 82°F or higher. Major regions of tropical cyclones are north and south central latitudes of the West Pacific, along the west coast of Mexico, the Caribbean, North Indian Ocean and south central latitudes of the Indian Ocean. The storm exhibits extremely low pressures with high winds and great rainfall blowing around a central eye. The

storm area may cover an area as much as 100 miles in diameter, but have a clear calm eye center from 12 to 15 miles in diameter. In regions hit by such great storms the storm rainfall may be a very significant portion of the annual total. The total rainfall for tropical cyclones may frequently average 5 to 10 inches, but under certain conditions recorded rainfall has measured 96.5 inches in 4 days (Trewartha 1954).

Besides the torrential rainfall itself, the storm causes major effects on the ocean surface. The winds of an approaching tropical cyclone cause the piling up of water against a coast into a hurricane tide which on a concave coast is usually from 3 to 10 feet high. In addition near the center of these intense storms a rapid uplift of water, as much as 20 feet in height occurs, and is known as a hurricane wave. Great avalanches of sea water pile up and are driven on shore by the gale winds. All these factors result in major inundation of low landmasses and coastal regions. Such storms are particularly destructive of atoll islands (Trewartha 1954).

ISLAND VEGETATION

Most attempts at climatic classification begin with vegetation analysis. Natural vegetation integrates the effects of climate better than any available instrumentation and for this reason is frequently used as an index of climatic conditions (Critchfield 1960). A lush growth of vegetation generally implies ample rainfall; however in endeavoring to estimate absolute values of rainfall, it should be remembered that 15 inches of annual rainfall may produce desert conditions in warm latitudes, but support coniferous forest growth in much cooler high latitudes.

Origin of Vegetation on Oceanic Islands

Man has been an important factor in determining the vegetation of oceanic islands. He has introduced new plants, destroyed much indigenous vegetation, and upset the phosphate balance by driving away the birds. Prior to the arrival of the European only the most habitable islands were disturbed by man. With the coming of the European, major altering of the natural features of drier islands resulted from the digging of guano for exportation; vast coconut plantations were established on the wetter islands. Coconut trees now so completely dominate the vegetation picture of tropical and subtropical islands that it is difficult to dispel the false belief that coconut trees are indigenous to the islands (Fosberg 1953).

The Second World War profoundly affected the atolls. Battles fought on islands such as Tarawa, Kwajalein and Wake left almost completely

bare land. In addition the tremendous movement of men and material across the island regions carried with it rapid introduction of many different and new species of flora to the islands.

Plant seeds are brought to islands by water, wind, birds and man either deliberately or accidentally. The plants that make up almost the entire indigenous floras of atolls, or low, islands are those that constitute the strand flora of high islands and continents. There are few species confined to, or principally found on atoll islands. Abundant seedlings from drift seeds of pioneer species develop continuously along the beaches. Compared with the high islands, the species of flora found on atoll islands is low, ranging from 3 to 150 on Pacific atolls to as many as 248 species on the Maldive Islands near continental land in the Indian Ocean. The greatest number of species occurs in the wetter islands (Fosberg 1953).

Atoll Island Vegetation

Atoll islands have a plant cover of strand type vegetation which at first hand appears very uniform; however, closer inspection shows wide variety and zonation of flora species. Major differences in vegetation character occur between islands in dry and wet climates. Dry islands have a sparse desert like vegetation of a few grasses, herbs, and dwarf shrubs which contrast sharply with the luxuriant jungles on atoll islands in the Central and Eastern Carolines and Southern Marshalls. Another important difference exists between the vegetation of small or narrow islets and those of larger landmasses; the vegetation of the islets is

much sparser in degree and variety because of the intimate and frequent association with sea water.

On most atoll islands there is a very definite vegetation zonation usually oriented from the outer beach to the inner, or lagoon, beach. The outermost zone contains a scrub reaching a height of 6 to 15 feet with smaller vegetation interspersed. On very narrow islets this may extend the full width of the land. Next there is a halophytic (salt tolerant) forest zone, which is ordinarily a narrow belt. The greater part of the interior is occupied by a more mesophytic (not adapted to any extreme) type of forest. On populated atoll islands this is usually made up of coconut plantations. On wetter islands the breadfruit tree is frequently grown in the interior. If the interior consists of marshes or swamps, mangroves and planted taro may be found. On the inner lagoon shore is a narrow strip of scattered trees and herbaceous growth (Fosberg 1949).

In general indigenous flora of atoll islands is more meager in variety to the eastward in the Pacific, and richer in the west because of the proximity there of larger landmasses with complex flora. Introduced flora is extremely limited on many small islands, and is unsuccessfully cultivated because of excessive salinity in the soil. Those that have been established are generally concentrated in the centers of the islands, or are very shallow rooted (Fosberg 1949).

Mesophytic conditions exist in direct proportion to the freshness of available ground water. As expected, the water is most fresh in the central portion of the atoll island, and accordingly supports mesophytic types of vegetation much more readily than the fringe areas. Physiological

dryness resulting from high ground water salinity is doubtless the limiting factor for the establishment of much plant life on low islands. The development of native agriculture (principally coconut, breadfruit, and taro) is coincident with the inner fresh ground water regions. On dry islands there is no agriculture (Fosberg 1949).

Both typhoons and tsunamis may send sea water completely over low coral islands. Tsunamis recorded on high islands have reached much greater heights than the highest elevation of most atolls. Some vegetation would undoubtedly be destroyed by such inundation but few facts are available. The coconut groves and breadfruit trees which are of primary importance to the native culture are usually badly damaged by the wind and wave forces, and the sea water.

Besides being a carrier of certain seeds to islands, birds are an important contributor of phosphate to the island soil, but may destroy the trees in which they roost by the high concentration of guano deposition, particularly during dry periods. Commonly phosphatic rock is formed at the site of former rookeries. This phosphatic rock may form a hardpan which hinders root growth or impedes water movement, forming shallow marshes (Fosberg 1949).

High Island Vegetation

A small amount of elevation allows a marked increase in the flora species quantity, and the vegetation becomes more mesophytic the higher the landmass. Thus high islands such as the Marianas support both a very much richer and more varied vegetation than the low atoll islands of

similar climatic and geographic circumstance. In addition, high islands are found in all latitudes while the vast majority of low islands are confined to the warm tropic and subtropic latitudes.

The high island vegetation has suffered most of all from the intrusion of the Europeans into oceanic regions. In the days of sailing vessels the isolated oceanic islands offered a welcome haven from the rigors and discomforts of sea life. By accident or intention sheep and goats were introduced to numerous islands with devastating results. Typical is the story of St. Helena in the Atlantic described by Carson (1951). About 1513, the Portuguese introduced goats onto the recently discovered island of St. Helena, which had developed a magnificent forest of gumwood, ebony and brazilwood. By about 1560 the goats wandered over the island by the thousands in flocks a mile long, trampling and eating the seedlings. Colonists aided the tragedy by the destruction of the mature trees. By the early 1800's the forests were gone and the island is described then as a rocky desert, with only remnants of the original flora persisting in the most inaccessible places. Recovery is slow even with the removal of the cause; in some cases impossible. From the island of Kahoolawe in the Hawaiian Islands drifts a red dust banner which may be seen for miles across the blue Pacific. Since 1891 a third of the island has been stripped of from 2 to 8 feet of red topsoil through the uncontrolled activity of goats and sheep. In less than 100 years the soil accumulation of a million or more years was blown away forever and the former green island became a bare, bald, forbidding land (Stearns 1940).

Wet tropical islands such as Truk present a rich variety of vegetation. Here the low sandy coastal areas are covered with forests of

coconut and shrubs. Mangrove trees grow within and below the intertidal zone in parts of the island. Fresh water marshes have dense growth of tall slender marsh seeds interspersed with scattered shrubs. The less precipitous lower slopes were cleared and planted to subsistence crops by the Japanese during the last two years of World War II and are now covered with various grasses and shrub vegetation. Also found on the accessible uplands are mixed forests of coconut palms and breadfruit trees. The summits and precipitous slopes support semi-open to dense forests of banyan and pandanus trees entwined with vines and scrubs (U.S. Army 1959).

On dry high islands in the warmer regions such as the Galapagos Islands in the Pacific and St. Helena in the Atlantic the zonation is principally of three types. The very arid low coastal regions to about 1500 feet elevation support little growth except thorny plants, cacti, and succulents. Higher up on the slopes are grasslands. Only in the highest regions are green thick stands of vegetation found.

On high islands composed of areas of rock of greatly different geologic characteristics, major contrasts in the vegetation may exist. In the Southern Marianas where substantial areas of limestone terrain and volcanic terrain occur side by side, the vegetation reveals this difference quite remarkably. Generally the geologic difference is marked by a thick, man-high sword grass growth on the volcanic terrain and dense jungle on the limestone areas (Cloud 1951).

The wet islands of northern latitudes, because of the cold, low light intensity, and extreme wind, present a much different picture than the wet islands farther south. At first glance the Aleutian Islands

present a barren desolate appearance due principally to an almost total lack of trees. Although the growth is low, it is in reality abundant. The beaches commonly are covered with strand wheat or wild rye grass reaching a height of 4 to 5 feet. Farther inland are thickets of willows, occasionally as much as 12 feet in height. During the short growing season from July to early September the meadows are aflame with color from wild flowers. The Aleutian heath, which covers extensive areas, consist mainly of a dense low tangle of tough-stemmed shrubs. On the still more exposed mountains, conditions may be severe for even the heath plants. Here occur extensive thick carpets of mosses and lichens. In the Aleutians this carpet is often as wet as a sponge. The lichen and moss carpet, and heath growth are commonly considered tundra. Higher up on the windswept peaks and in the most exposed places the ground surface is bare (Collins *et al.*, 1945).

Vegetation as an Indicator of Fresh Ground Water

In most arid regions plants that feed on ground water stand out in sharp contrast to those that do not. However, as the climate progresses into a more humid nature the control and necessity of the water table becomes less rigid. Certain species of flora become dormant or die when soil moisture is inadequate; others utilizing ground water continue to grow actively during the dry periods (Meinzer 1927). It is principally on the low islands that certain common types of vegetation may provide indications of the nature of the ground water.

The presence of halophytes (salt tolerant plants) may indicate saline ground water. Even though the roots of such plants may be in a

saturated soil, the highly concentrated salt content of the water causes it to be physiologically dry to plants. On halophytes transpiration control adaptations such as waxy leaves frequently occur.

Perhaps the hardiest large indigenous growth found on the islands is the Pisonia tree; large dense groves of these trees are found on islands of moderately heavy rainfall (80 to 110 inches per year). They seem to survive even on islands so small that a fresh water lens does not exist such as tiny Rose Island (about 200 yards by 240 yards in size). Here the Pisonia trees with their creamy white bark, large light-green leaves and twisted stems attain heights of 85 feet and girths of 25 feet. Sprouts of new growth can form from practically any part of the tree in the usually damp soil; sprouts from roots, branches, stubs, and fallen trunks form luxuriant tangles of stems and branches. But in this seemingly lush environment, because of the lack of a fresh ground water supply, coconut trees have not survived well (Sachet 1954).

The pandanus tree is a tree of medium dimensions and tropical appearance. Long slender branches are irregularly arranged. Long strap-like leaves are spirally inserted at the branch ends and have sharp marginal serrations. The pandanus probably provided the original food supply in the atoll islands; but when the coconut became plentiful, the pandanus became of secondary importance. The pandanus has a greater tolerance to drought and salinity than the coconut palm, but in the most unfavorable conditions it will succumb (Catala 1957).

The familiar coconut palm is certainly the most frequent and probably the most useful indicator of marginal ground water conditions. The coconut palm is a halophilous plant with some salt tolerance, but with

a limit; however, even brackish water will enable it to survive during a drought. During a drought the leaves dry and nuts no longer grow; these return with rain. Palms mark droughts by narrowing of the trunks during the dry period. When good conditions return the newer higher growth is expanded. Thus the continuity of trunk thickness may indicate the drought history of a tree (Catala 1957).

The coconut palm has a radiating, highly developed root system, the roots being constantly renewed. Ground conditions must be well-drained; standing water is fatal. Deep sandy soil with fresh to brackish water is best for palm growth (Catala 1957). On wet islands the palm thrives on sandy shores right up to the beach line. The palm, except for the small yuraguano or fan palm, is a reliable indicator of ground water at least brackish in quality (Meinzer 1927).

The distribution of the breadfruit tree, even though it is not normally a phreatophyte, is closely related to salinity in the ground water. It is much less resistant to drought and salinity than the palm. The breadfruit tree does not appear to survive where the ground water has a salt content higher than 200 - 400 ppm (parts per million) of chloride (Wiens 1962).

Banana and papaya trees, and taro plants require even fresher ground water than the breadfruit tree. The presence of these plants indicate a ready supply of ground water of very low salinity.

Vegetation as a Source of Water

In an emergency liquids provided by many types of vegetation [illegible]

on oceanic islands can provide a safe and adequate substitute for water.

The most suitable source of a palatable fluid is the coconut palm. Natives frequently use the liquid of the unripe (green) coconut as an important source of supplemental water. The liquid is sterile and if obtained from very young nuts has anti-scorbutic value. The nuts contain from a pint to a quart of sweet, pleasant liquid which is cool if the nuts have been hanging in the tree or stored in the shade. A drinkable sugary sap may also be obtained directly from the palm itself, either from the flower stalk or the bole of the tree. A quart or more of sap daily may be obtained by cutting the end of the flower stalk and renewing the cut every 12 hours. The flow of sap from the bole can be started by bruising a lower frond and pulling it down so that the tree will bleed at the injury; the sap will run down the trough-like frond and can be collected (Naval Institute 1959).

The hollow stems of bamboo may frequently contain water. This can be determined by shaking the stem; if water is present, a cut just above the joint will allow it to run out.

The leaves of the pineapple-like Bromeliads, which are found growing above the ground on the trunks of tropical trees, are good sources of water. The leaves of these plants are regular funnels forming reservoirs of water at the central stem. A single plant may hold several pints of rain water.

Many large vines or lianas found in the tropics contain a pure water sap which is slightly acid. Not all vines contain water, however; and the fluid from some is more palatable than others. The procedure for obtaining the sap is to cut the vine high, holding the severed end

elevated. Then the vine should be cut off close to the ground giving a water tube six to seven feet long. When water stops dripping from the lower end a new cut off the top of the tube will cause it to drain again (Naval Institute 1956).

On many arid or semi-arid islands the fleshy stems or leaves of succulent plants, especially the cacti, can provide a liquid adequate for survival. The fleshy material can be squeezed or mashed, and the liquid strained and drunk with safety. Apparently the Indians living on barren dry San Clemente Island off the coast of Southern California considered this as a primary water substitute during the dry summer months. The liquid was obtained by mashing the succulents (abundant "ice plant") in a bowl with a small hole in the bottom through which the liquid drained.

SEA WATER-FRESH WATER RELATIONS IN THE GROUND

The Ghyben-Herzberg Theory

In all except the most impervious landmasses, rainfall will infiltrate and percolate downward to a degree dependent on the permeability of the geologic material. At some point in its movement through an oceanic island, the fresh water must encounter sea water. The contact envelope thus made normally constitutes a unique limiting boundary condition for fresh ground water occurrence in the small island. Exceptions may be found in extremely pervious low-lying small sand islands and rock islands containing wide fractures or cavernous openings, but generally the salt-fresh water boundary is well-defined physically within the landmass. Even on a dense bedrock coast, the bay areas are frequently composed of pervious deltaic alluvium or beach sediment which foster similar boundary conditions between fresh water and sea water.

Records of many early futile attempts to obtain fresh ground water from coastal aquifers and islands indicate that the sea water-fresh water relationship was not at all understood prior to the Twentieth Century. The practice of drilling deeper for fresh water was frequently attempted even after sea water was encountered. In some geological situations along a marine coast such an endeavor can be successful, but this is a relatively infrequent phenomenon (Brown 1925). In some geological formations of very high permeability the opinion was too easily formed that fresh ground water necessarily terminated at sea level. It was not until 1[illegible]7 that Badon Ghyben, a Dutch captain of engineers working on the sea coast

of Holland, first discovered that the depth of sea water was a function of the height of the water table above mean sea level. In 1900, Baurat Herzberg of Berlin, drilling wells on the East Friesian Islands off the coast of Germany, found the same relations, apparently without knowledge of Ghyben's work. Hence, the basic theory for the sea water-fresh water relation is termed the Ghyben-Herzberg theory.

The Ghyben-Herzberg theory is based on the principle that fresh water, being less dense than sea water, will tend to float on top of the sea water. This is in fact essentially what occurs. In a small island or narrow landmass of pervious material a well-defined lens of fresh water is found below the surface of the ground and on top of the sea water as shown on Figure 8.

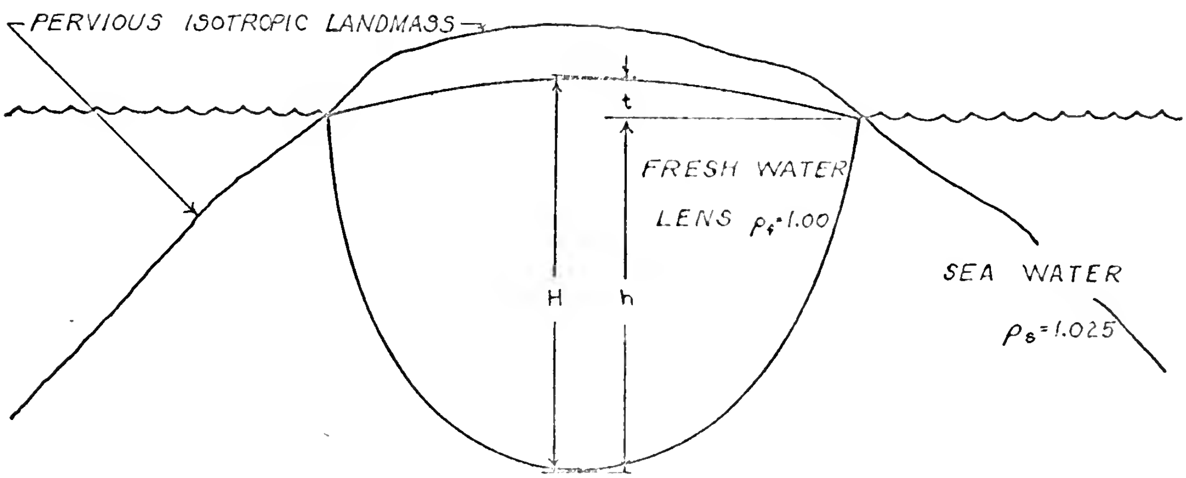

Figure 8. The Ghyben-Herzberg Theory

The total height, H, of fresh water displaces the lesser height, h, of greater density sea water - essentially a unique application of Archimede's principle. The difference, t, will be the elevation of the

ground water above mean sea level. Assuming the specific gravity of fresh water to be ρ_f and sea water to be ρ_s, then:

$$H \rho_f = h \rho_s \quad \text{and} \quad H \rho_f = (h + t) \rho_f$$

$$\text{combining equations gives} \qquad h = \frac{t \rho_f}{\rho_s - \rho_f}$$

The specific gravity of sea water, ρ_s, varies, but averages about 1.025. The specific gravity of fresh water, ρ_f, may be taken as 1. Using these values it is found that $h = 40\ t$. Thus it is found that the lower boundary of fresh water is 40 feet below sea level for every foot above sea level the water table occurs. This relation has been well substantiated by field measurements (Brown 1925).

Even though the basic veracity of the Ghyben-Herzberg theory has been well-demonstrated, it fails to take into account the influence of flow. It has, in effect, assumed either static equilibrium, or horizontal flow. The relation actually is not a static one, and cannot be, if the fresh water lens exists at all; neither is the flow horizontal since both the upper and lower fresh water boundaries converge to a seepage periphery. In a strict sense then, the measurement of depth relation must be made at terminal points of an equipotential line, and not in a vertical line (Todd 1953). This results in a vertical depth to the interface being actually somewhat greater than that determined solely by the basic theory. The diffusion at the interface tends to obscure this difference; for this reason early observations did not detect it. For flat gradients the difference remains small, but for steep gradients large errors may be

incurred when the flow net is not considered (Todd 1959). The partial flow net shown on Figure 9 for a theoretical island composed of isotropic material serves to illustrate the differences between the depth to the interface by the basic Ghyben-Herzberg theory and that of the more correct application of dynamic equilibrium.

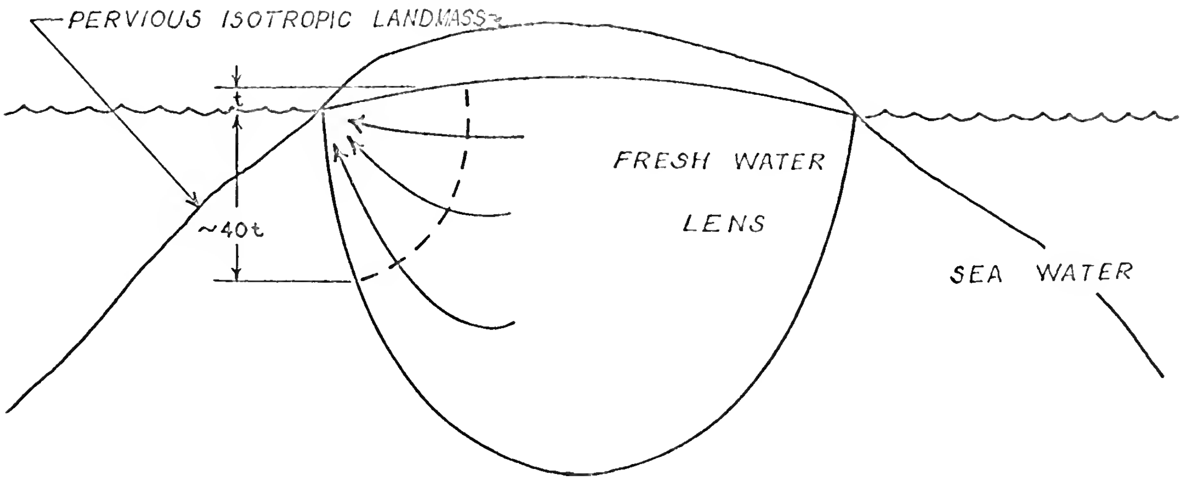

Figure 9. Concept of Dynamic Equilibrium

The Sea Water-Fresh Water Boundary (Interface)

The shape of the interface is concave with respect to the fresh water. At the ground water surface the sin of α, the angle to the horizontal, is:

$$\sin \alpha = \frac{dh}{ds} = \frac{v}{k} \quad \text{(from Darcy's equation,}$$

$$v = k \cdot \frac{dh}{ds} \text{)}$$

The phreatic surface elevation decreases in the direction of flow, hence the interface rises as shown on Figure 10. The slope from the

horizontal is given by

$$\sin \beta = \frac{\rho_f}{\rho_s - \rho_f} \cdot \frac{dh}{ds} = \frac{\rho_f}{\rho_s - \rho_f} \cdot \frac{v}{k}$$

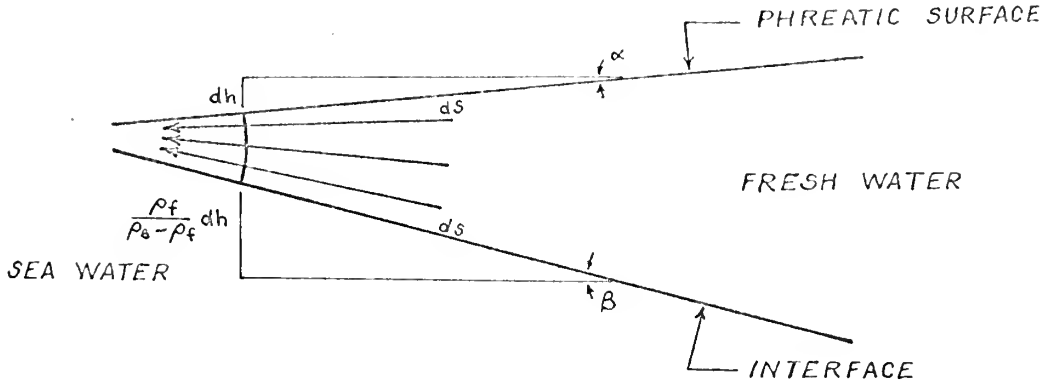

Figure 10. The Shape of the Interface

The boundaries converge, but accomodate the same flow of water, hence the velocity must increase. It then follows, since all other factors remain constant, that the angles must also increase resulting in the concave interface (Todd 1959).

On coasts composed of porous sand, the interface has a well-defined slope upward toward the sea in a curve closely approaching a sinusoid. The flow of the fresh water is upward along this face. The more porous the material, the flatter the curve becomes. In the fractured limestones of the Florida Keys and the very porous basalts of the Hawaiian Islands the fresh water lens is a very thin, almost flat sheet (Brown 1925).

Most small oceanic islands consist of relatively permeable sand, lava, coral, or limestone. Sea water is in contact with fresh water on

all sides and completely underlies the island at some depth. Inflow of fresh water occurs only as a result of rainfall percolation to the water table. For the simplified circular island of Figure 11 an approximate boundary of equilibrium, based on the parameters of rainfall, permeability and island size, can be determined by employment of the Darcy equation and the basic Ghyben-Herzberg theory (Todd 1959).

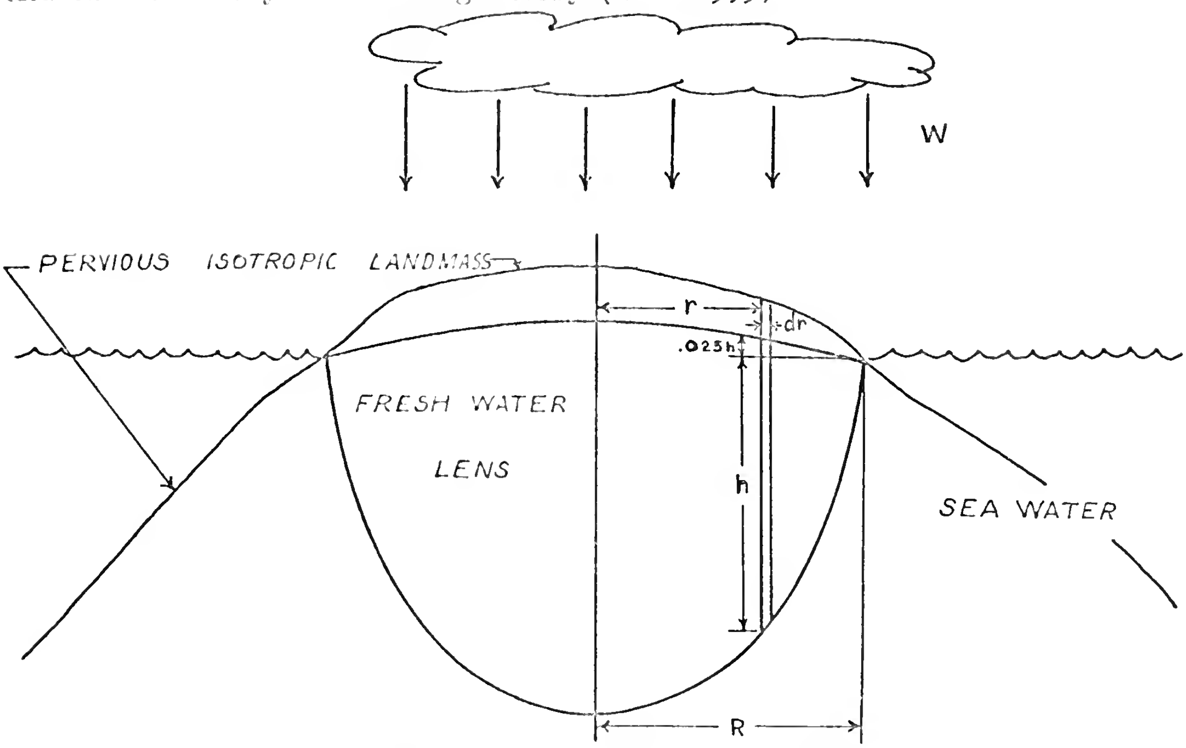

Figure 11. Determination of the Fresh Water Boundary

If effective rainfall recharge occurs at a rate W then the inflow rate is

$$Q = \pi r^2 W$$

and the outflow at a distance r is

$$Q = 2\pi r k \ (1.025\ h) \ \frac{d\ (0.025h)}{dr}$$

Equating these equations, integrating and applying the boundary conditions $h = 0$ when $r = R$, then:

$$h^2 = \frac{W}{0.0512k} (R^2 - r^2)$$

Thus the depth of sea water is a function of rainfall recharge, landmass size, and permeability. It is apparent that increasing the rainfall recharge increases the depth of fresh water, and that increasing the permeability decreases the depth. Good water, in small quantities, may be obtained even on very small bedrock islands where there is a cover of pervious material permitting infiltration of rain water. Off the coast of New England (annual rainfall about 45 inches) such an island of an acre, or about 250 feet in diameter, will usually supply sufficient water for the ordinary requirements of a household (Brown 1925). The available supply should increase in considerably greater ratios for a larger island as the relative losses about the perimeter become smaller. Islands composed of very porous sands are generally underlain by sea water at slight depth and may contain only brackish water up to the level of the water table. If water bearing rocks extend to any considerable depth the island will be underlain with sea water and deep wells are not usually productive of fresh water. In the Southern Marshalls with a rainfall of over 60 inches per year, infiltration is adequate to maintain a permanent lens if the island is at least 0.1 square mile in area. This size apparently provides sufficient catchment area and adequate width for damping of tidal fluctuation (Arnow 1954). In the Gilberts, with rainfall greater than 44 inches per year, islands wider than 1000 feet

produce good water at their centers (Wiens 1962).

The magnitude of tidal fluctuation in the basal ground water body of the small oceanic island is inversely proportional to the distance to the shoreline, and directly proportional to the permeability of the landmass. The amount of dampening of the tide observed in a well is roughly indicative of the freshness of the water in the well. Arnow (1954) found the following relations in the atoll islands of the Northern Marshall Islands:

Island	distance to lagoon shore	mean tidal range-well	mean tidal range-ocean	range ratio	chloride content
Ailuk	115 ft.	0.32 ft.	4.0 ft.	.08	272 ppm
Lae	1035	0.16	2.1	.08	15 ppm
Ujelang	140	0.20	1.7	.12	100 ppm
Wotho	330	0.22	4.8	.05	130 ppm

Relatively impermeable beach rock serves as a barrier to the outflow of fresh water and inflow of sea water, which are particularly important features at the thin sensitive edge of the lens. Lines of old beach rock buried in the interiors of small coral islands may make similar echelons of barriers enhancing the development and maintenance of a fresh water lens. Such a boundary effectively reduces tidal fluctuation (Wiens 1962).

Higher temperatures greatly increase the rate of percolation, allowing ground water to seep seaward more quickly. Field tests show that a change of temperature from 32°F to 75°F will practically double the ability of water to pass through soil. This fact, combined with the effects of high summer evaporation - transpiration, and the usually low rainfall in a temperate climate, can cause depression of the water table and

consequent reduction of lens size in the very small island during the summer period when the sea water temperature may be 20°F higher than in winter. Generally the annual variation of ground water temperature in a larger landmass is negligible below a depth of 30 feet, and except for the most pervious conditions, the practical effect is insignificant. A marked difference in flow does exist, however, between two landmasses of similar geological material, but different annual temperatures.

Theoretically the interface is a flow line with no flow across the surface. However, in fact the interface consists of a relatively narrow mixing zone. This zone results from dispersion in the porous material, from fluctuation in the interface due to tides, water table fluctuation and molecular diffusion (Todd 1959).

The rate of molecular diffusion between fresh and sea water is proportional to the concentration gradient. The initial contact has a high diffusion rate which becomes smaller as the diffusion zone increases and the concentration gradient decreases. Because diffusion rates are smaller than usual ground water velocities at the interface, the diffusion zone is limited to a narrow band (Todd 1953).

In crystalline rocks and in indurated sedimentary rocks, where the ground water circulates through joints and open fractures, the zone of contact between sea and fresh water is undoubtedly more irregular than in homogeneous pervious material. Fissures filled with sea water may interlace with those containing fresh water and diffusion is generally greater. But even here the nature of the interface remains the same - the fresh water is almost invariably superimposed upon the sea water with a definite boundary (Brown 1925).

In a homogeneous material the flow within the lens moves seaward, with the seepage line of outflow occurring at sea level. Because of tidal fluctuation and wave action, the zone of seepage is frequently a zone of maximum diffusion of fresh water and sea water. However, the continuous outflow of fresh water through this zone constantly purges it, and at low tide the salinity of the outflow is minimal. If no confining geological structures exist, except for a relatively small quantity lost through interface diffusion, all ground water will escape from the landmass at the sea level seepage face.

Artesian Ground Water

Artesian water may occur where permeable material is overlain by an impervious bed dipping seaward at a slope greater than the hydraulic gradient (Brown 1925). This condition is illustrated in Figure 12.

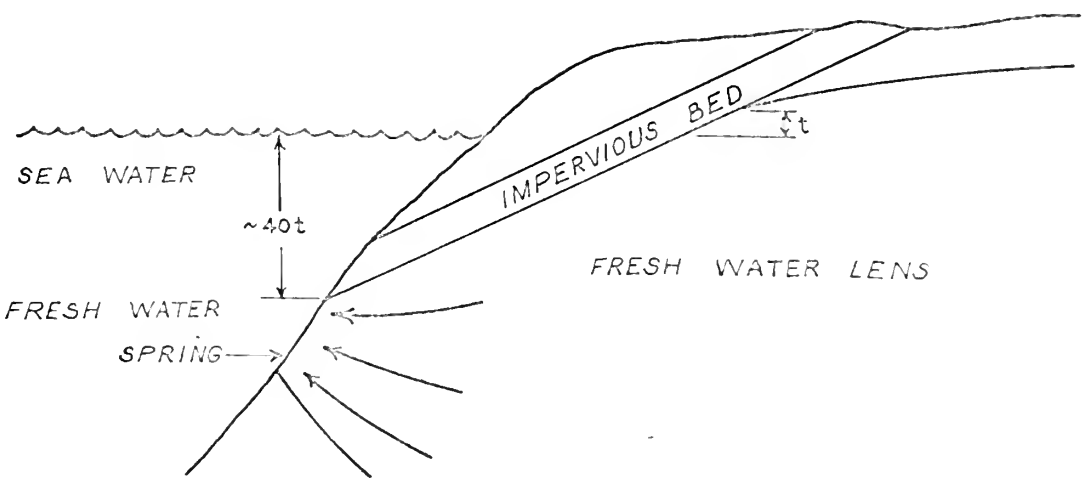

Figure 12. Submarine Spring Formation

If the overlying bed extends below sea level the water [illegible]

either over the top above sea level, or emerge as a fresh water submarine spring below the sea (Meinzer 1930). Which action occurs depends on the relative limits of elevation of the confining bed above and below sea level. If the height of the top of the bed above sea level is greater than about 1/40 the depth of the bed, the fresh water will flow out beneath the sea. If the bed extends a great depth below the sea, overflow will occur above sea level.

If the aquifer is confined between impermeable beds which dip seaward the same relation for outflow exists. This situation as shown on Figure 13 is very analogous to a real U tube in which one arm is the sea water and the other is the aquifer.

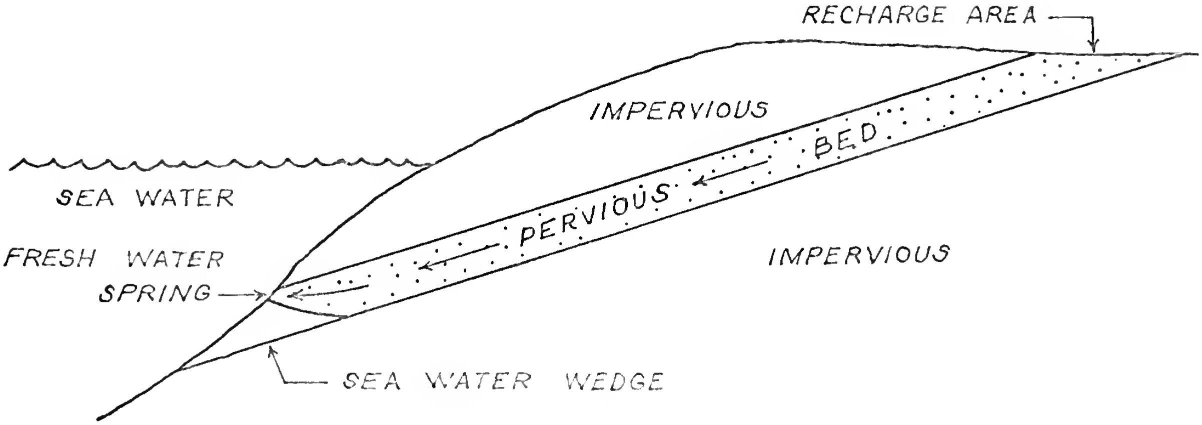

Figure 13. Sea Water Wedge in Pervious Aquifer

At the bottom of such an aquifer, whether or not the fresh water emerges from the sea, a sea water wedge will exist. If overflow occurs above sea level the interface in the wedge will be horizontal at a depth such that the piezometric pressure equals the water pressure computed from seaward. If the fresh water emerges as a spring a different form of wedge will result. If a seaward fresh water flow of q cubic feet per second/foot of ocean front exists then the following approximate relation

described in Figure 14 holds (Todd 1959):

$$q = 1/2 \quad \frac{(\rho_s - \rho_f)}{\rho_f} \quad \frac{Kb^2}{L}$$

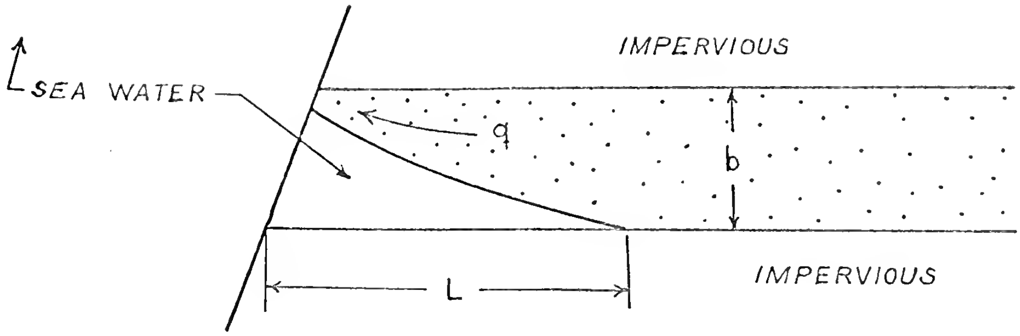

Figure 14. The Length of the Sea Water Wedge

This equation can also be applied to unconfined aquifers by replacing b with the saturated thickness, if the flow is essentially horizontal. Tests at the University of California have demonstrated the validity of this equation (Todd 1959).

Sea Water Contamination

The presence of sodium chloride is both the paramount feature of, and principle human objection to, sea water. Since the chloride radical is so characteristic a constituent of sea water and can be determined very quickly and accurately by simple chemical tests, it is usually used as the criterion to judge the amount of contamination of fresh water by sea water. But in accepting the presence of chloride as an indicator of sea water discrimination must be used, for the chloride may come from

sources other than the sea. In some regions it may be leached from the rocks and be a normal constituent of the ground water. A small amount of chloride is invariably carried shoreward as wind-blown salt spray. The most important source of chloride in fresh ground water, other than sea water, is sewage. However, seldom does the aggregate of these sources add chloride in excess of 125 ppm. Normal sea water contains about 20,000 ppm of the chloride radical. Hence, heavy concentrations of chloride are obvious in their source, but smaller indications of chloride deserve closer analysis to determine more positively the source of the contamination (Brown 1925).

The extreme upper limit of chloride for drinking water is about 1,000 ppm, approximately 1/20 that of sea water. The U. S. Public Health Service has adopted a safe upper limit of 250 ppm. It appears that at about 400 ppm the salt taste of water becomes most noticeable and even without testing, humans discontinue its use for drinking purposes.

The tolerance of vegetation to salt in water varies greatly from almost no tolerance to complete tolerance in certain tideland growth. Under slightly saline conditions many plants will grow, but their quality may be greatly impaired.

Ground Water Exploitation and Safe Yield

When it is found that a fresh water table does exist in a landmass, even though the water level be as little as a foot above mean sea level, it may be assumed that a considerable reservoir of fresh water lies within the ground. However, it must be recognized that this reservoir represents a natural balance of hydrologic influences which is affected when an

outside influence is introduced. Accordingly, removal of ground water causes the system to attempt to reach a new balance.

Removal of ground water at a rate faster than replenishment, or even at the expense of replenishment, results in a lowering of the water table, and a consequential raising of the interface at a ratio of about 1 to 40. The movement of the interface lags behind that of the water table because of the greater distance involved to reach the new equilibrium, hence this inevitable result may not be recognized immediately. It is further apparent that a rapid concentrated withdrawal of fresh water will cause a local effect more rapidly than a drawdown of the same quantity which is distributed over the surface of the lens. The result of drawdown is an intrusion of sea water within the lens. Plate VIII illustrates the effects of drawdown by several different methods utilizing the same withdrawal rate. It is obvious that a rapid concentrated drawdown will quickly destroy the usefulness of a well by the development of a contaminating sea water cone. The intrusion cone will intersect the cone of depression sooner if the withdrawal point is deeper. Hence, the safest method of withdrawal of fresh water from the lens is that which removes it uniformly at the lens surface.

If the need for a maximum supply of fresh water is immediate, and little importance is assigned to future use of the aquifer, then full exploitation may be advantageously undertaken. However, once the sea water has permeated through the land mass, restoration of a salt free ground condition may take years, dependent on the occurrence of rainfall and permeability of the land mass material. Even if the center of the withdrawal zone is restored, the diffusion zone is greatly thickened, and

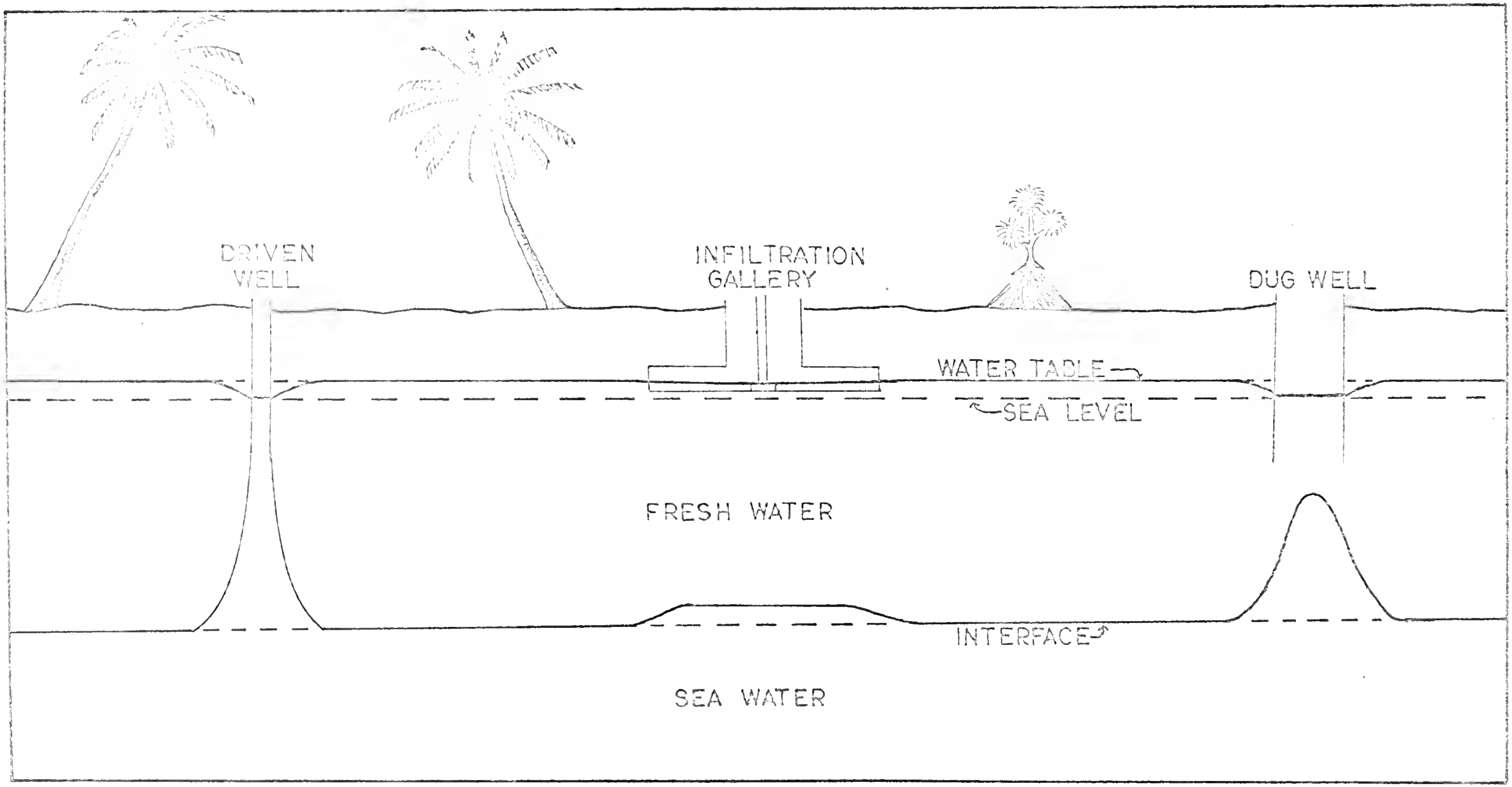

PLATE VIII WELL INTRUSIONS FROM SAME WITHDRAWAL RATE

DRAWN FROM U.S. ARMY (1956)

the water at any given level will remain more saline than before the intrusion occurred. The intrusion of sea water is not normally considered a practical reversible process (Ohrt 1943). Full depletion of the fresh water lens was necessarily effected to great advantage in the Pacific Islands during World War II. Even in the Hawaiian Islands this lens storage became an important factor in sustaining the vastly increased water demands there because of the war activity. Under certain conditions, full depletion of the lens may be necessary, but for continued use, a minimum disturbance of the natural balance is the safest procedure. This allows both a reserve storage for contingency and lessens the possibility of sea water cone intrusion at well sites. When the lens is reduced, the "factor of safety" is reduced, but a greater efficiency in the use of ground water may be accomplished because of a consequent reduction of seepage to the sea (Jacob 1957). Both considerations must be evaluated in perspective with water demands and the size of the available fresh water lens. In any case the smooth configuration of the surface of the lens should be maintained.

The most successful ground water collection systems consist either of fields of low capacity shallow pumps (Riddel 1933), or horizontal infiltration galleries at about sea level (Ahplanalp 1945, Stearns and MacDonald 1942). Where the geology allows economic construction of the latter type, as in permeable basalt or low atoll islands, this is generally most effective. In deep unconsolidated material pumps are more generally used.

The safe yield is generally defined as that amount of water which can be withdrawn annually without producing an undesired result (Todd 1959).

Most frequently the limiting undesired result in the small oceanic island is the contamination of the aquifer by sea water. Consequently, if continuing use is to be made of a ground water supply which may be so contaminated, a discreet approach must be made to determination of the safe yield. A state of overdraft can be disastrous, resulting in total loss of the well or pumping system aquifer.

A reliable value of the safe yield can only be ascertained after pumping experience has been gained; however, a reasonable initial estimate of pumping rate should be made. The general basis for safe yield is that the withdrawal cannot exceed the net ground water recharge, usually computed on an annual basis. However, it is apparent that withdrawal must not take all the recharge, even if it could be skimmed evenly off the lens, in order that the lens be retained. Some recharge water is necessarily wasted to the sea at the edge of the lens. The safe yield would then appear to be something less than the net recharge. Theoretically the recharge might be determined from the annual precipitation, but in practice, except for small well-defined recharge areas, the evaluation of the modifying parameters is extremely difficult. In addition, the withdrawal is seldom uniform over the recharge area, but is concentrated at local points of pumping.

The safest first estimate of yield is the yield which results in a drawdown preferably not less than about a half foot above sea level. This eliminates the danger of a sea water cone intrusion into the pumping cone of depression. A positive value of ground water elevation based on the desired ground water reservoir retention can be selected, and observations of yield versus ground water fluctuation made.

In the development of ground water use for the first time, it may be expected that several years will be required for a new state of equilibrium to be reached even if the yield is maintained constant.

Overdraft conditions may occur rapidly in the small landmass. If overdraft occurs, the resultant contamination will exist for a long period, probably years. Hence, the effect of withdrawal of water should be closely watched until it is certain that a new safe stable equilibrium of the lens has been reached.

FRESH WATER OCCURRENCE ON ISLAND TYPES

The Basic Island Types

It is considered that the small oceanic islands may be categorized as five basic types. The division made is primarily based on significant hydrogeological differences. The climate necessarily creates subtypes within each basic division. These subtypes will not be discussed individually; however, it is believed that the difference in hydrologic characteristics because of climatic variation between the models given and climatic subtypes will be fairly obvious. The five basic types of small oceanic islands are:

1. low atoll islands
2. raised atoll islands
3. high basalt volcanic islands
4. high andesite volcanic islands
5. raised limestone-volcanic islands

The raised limestone-volcanic island is, in simple model terms, a composite form of the raised atoll, or limestone, island and a high andesite volcanic island. Therefore in the discussion which follows only the low-lying atoll islands, the high basalt volcanic islands, and the raised limestone-volcanic islands will be specifically described.

The Low Atoll Island

General Character

Essentially, the low-lying atoll island is a pile of calcareous

sand and boulders heaped up on the reef platform, the top of the reef which characterizes the atoll. The basic features of the island are shown on Figure 15.

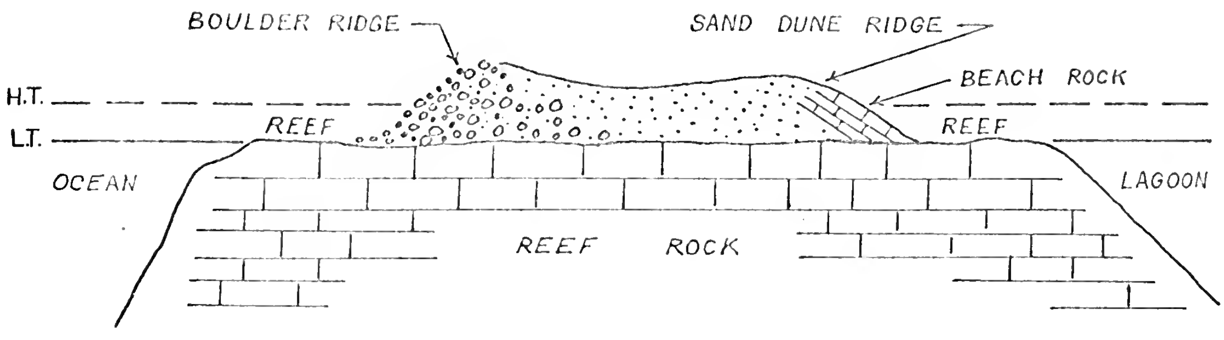

Figure 15. Generalized Section of Atoll Island

Commonly the island projects no more than a few tens of feet above sea level; however, the aeolian dunes of the Bermudas are as much as 200 feet high. Except for the Bermudas, the reef rock platform on which most atoll islands lie may be considered to be at about the low tide level. In some cases the core of the island may be remnants of elevated (probably about 5-1/2 feet) reef rock from a higher sea level stand. Also as a variation, the island detritus may "spill" off the reef rock platform on the lagoon side. The possibility of variations may be better understood if it is remembered that geologically the islands are an ephemeral feature. Great changes may be wrought by a single typhoon or tsunami.

The primary hydrological characteristic of the atoll island is its extreme permeability. Even on beaten paths rainfall seldom travels more than a few feet before sinking into the ground. Generally the ocean side of the island is made up of large size pieces of rock ripped from the reef and washed up during storms. The lagoon side is composed of finer

material and consequently is less pervious than the seaward side. On either beach relatively impervious beach rock may develop.

The interior of the island is generally depressed in elevation from the shoreline ridges of boulders and sand. On some islands, sections of the interior may contain a relatively impervious strata of phosphate rock. Because of its transitory nature, lines of old beach rock may also be found in the interior.

All atoll islands are in the tropics or subtropics; however, because of the wide variance of rainfall between islands, they may be covered with dense jungle-like growth or support only sparse grass.

Natural Fresh Water Occurrence

Streams. On the atoll island there is no running surface water, except perhaps during typhoons. All rainfall reaching the ground rapidly infiltrates to become ground water.

Springs. Fresh water springs may be found along the beach on the wetter islands during low tide. These springs represent the outflow at the edge of the Ghyben-Herzberg lens. Other types of springs do not occur.

Lakes, lagoons and ponds. Standing bodies of water are infrequent but they do occur. The most common is the small pond or pool which may form in the interior of the island where the land surface dips below the water table. Wilkes (1845) reported that fresh water on Aratika Atoll in the Tuamotus (rainfall about 60 inches per year) was procured from a large pool about 50 feet in diameter and of considerable depth.

Occasionally a lagoon may be sufficiently isolated from the sea to become what might loosely be termed a fresh water "lake." According to Wiens (1962) Washington Atoll in the Line Islands is said to contain a beautiful fresh water "lake" surrounded by luxuriant growth.

Clipperton Island, an almost atoll in the eastern Pacific, presents an interesting example of a sea water lagoon becoming fresh. During the past 100 years the rim of the atoll has been alternately closed and opened several times with the lagoon freshening with each closure and becoming salty with each opening. The annual rainfall, estimated at over 200 inches, is apparently sufficient to freshen at least the upper layer of the two square mile lagoon. In 1943 the lagoon was closed and the surface water was essentially fresh at a total salinity of 1200 ppm. At a depth of about 60 feet of water in the lagoon becomes black and opaque, and is full of hydrogen sulfide, a product of organic matter that died as the result of past violent changes in lagoon salinity (U. S. Navy 1959, Sachet 1962).

On Christmas Island in the Pacific a peculiar microclimate effect results from the fresh water-sea water density relationship. A small, but hot, lagoon about three feet deep exists. The water of the lagoon has a surface temperature of 85°F, but a bottom temperature of 102°F. The anomalous temperature structure is due to a fresh water blanket floating on top of a salt water lagoon which allows radiation to pass through the fresh water into the deeper layers. The salt water is heated, but little heat is transfered out since the upper fresh water layer is the sole beneficiary of normal cooling by evaporation. There is no heat transfer through diffusion, and conduction in the still lagoon is inadequate

to distribute the temperature (Northrop 1962).

<u>Swamps and marshes</u>. A common feature found in the interiors of atoll islands is the mangrove depression. This is a low swampy area extending to or below the water table. The bottom may be either mud or rock (U. S. Army 1956).

A characteristic of many of the larger atoll islands is the presence of marsh depressions of irregular shape, and with mounds between or around them extending several feet above the surrounding ground level. These undoubtedly are ancient taro pits, dug to the fresh ground water long ago and now abandoned (U. A. Sarmy 1956).

In the interiors of some islands phosphate rock creates a hardpan immediately below the surface impeding the downward movement of water. Local temporary marshy areas may be formed in such regions.

<u>Ground water</u>. Certainly the most important occurrence of fresh water on an atoll island is the ground water. If the rainfall, permeability and size of the island are in an adequate relationship a Ghyben-Herzberg lens will develop. Characteristically the lens will be asymmetric, being thicker on the lagoon side than on the more pervious seaward side. On the atoll island the water table is seldom more than a foot or two above sea level; according to the Ghyben-Herzberg theory the body of fresh water then probably extends no deeper than 40 to 80 feet at the point of highest water table. Voids and lack of uniformity in the permeability of the land-mass material may greatly disrupt the theoretical configuration of the lens. On Onotoa Atoll in the Gilberts (annual rainfall 44 inches) a well in the center of an island wider than 1000

feet has a good chance of producing a fairly continuous water supply to a native population (Wiens 1962). In islands of the Marshall Group where rainfall is greater than about 54 inches annually conditions are similar with a permanent lens existing when the island is at least 0.1 square mile in area (Arnow 1954).

The beach rock found on both ocean and lagoon shores is much less permeable than the uncemented sediments. Where there is beach rock at the shore, either at the surface or buried under sand, a barrier should be formed to the outflow of fresh water from the island. If the reef platform is relatively impermeable and the beach rock extends to it, the effect becomes even more important, causing a high head, very little tidal effect, and low salinity. Beach rock relating to old shorelines presently buried in the interior of an island may make similar barriers resulting in the separation of two or more independent fresh water bodies if the reef platform is impermeable. Such layers of beach rock might also result in the perching of thin bodies of fresh water above sea level (Cox 1951).

Conscious use of ground water is made by the natives of many Pacific islands in growing taro. Taro is grown only in a fresh water muck, and probably only where the water has movement. With no surface streams the islanders have met the requirement by excavating pits some 5 to 6 feet from the ground surface to the water table. The tidal fluctuation of the water table apparently induces sufficient movement of the water (Cox 1951).

Ground water may be recovered from atoll islands by dug wells, driven wells, or infiltration galleries. Of these the dug well is the

simplest and was the first to be developed in the atoll islands. Since the well should not penetrate more than about a foot below the water table, the hole is normally not deep. A driven well may be used, but then pumps must be used and the danger of overdraft becomes great.

The most effective ground water withdrawal in the atoll island is by means of an infiltration gallery. An infiltration gallery consists of a tunnel, trench or permeable conduit paralleling and intersecting the water table. The floor of the water passageway is graded so that water flows to a central sump. The sump is lined so that water flows into it only from the passageway, not from the water table directly. The water then is skimmed off over a wide area thus distributing drawdown. Trenching can easily be done with a bulldozer or trenching machine and large diameter pipe installed for easy cleaning. The system should be placed where the lens is thickest (U. S. Army 1956).

Rain water catchment. Especially on the drier atoll islands, but on even the wettest islands, rain water catchment constitutes an important water supply. Rain water is generally preferable to ground water for drinking.

In the simplest native practice, the coconut palm or the pandanus tree has been the common rain catch. In the coconut palm a considerable part of any intercepted rain is deflected to the trunk or bole by the channeled midribs of the numerous fronds. To gather this water, an inclined groove is scored around the lower part of a leaning tree; then the water flow running down the bole drops into a convenient receptacle, originally an old canoe, most probably. With such a simple arrangement, a single palm can yield sufficient fresh water for a native family during

most of the year on the wetter islands (Piper 1946).

The more common practice today is to catch the runoff from roofs, conveying the water into cisterns. The roof of a small (500 square feet) building will provide about 300 gallons of fresh water for every inch of rainfall. Airfields make excellent catchment surfaces and, if coupled with large enough storage facilities, can provide an adequate water supply for a large group of personnel. Water storage requirements must be developed utilizing mass diagram techniques with probable rainfall and usage data.

Typical Low Atoll Island: Lae, Marshall Islands

The following information is from U. S. Army (1956).

Lae Island, one of numerous atoll islands in the Marshall Group, lies at 8°56' North and 166°16' East. Lae is shaped roughly like a long triangle with a maximum width of 2,500 feet and an area of 0.3 square miles (Plate IX). The island lies on the east side of a small, almost circular atoll of the same name. Of the numerous islets of Lae Atoll, Lae Island is the largest and most populated.

Most of Lae Island is planted to coconuts, but the east point is very rocky and most of it is thickly wooded. The west point is dry and sandy, covered by a sparse but tall scrub. A native village is strung out along the lagoon shore.

The climate of Lae is tropical oceanic, being moderately warm, usually between 80° and 90°F, with little variation. The island lies in the trade wind belt with the prevailing winds from east to northeast.

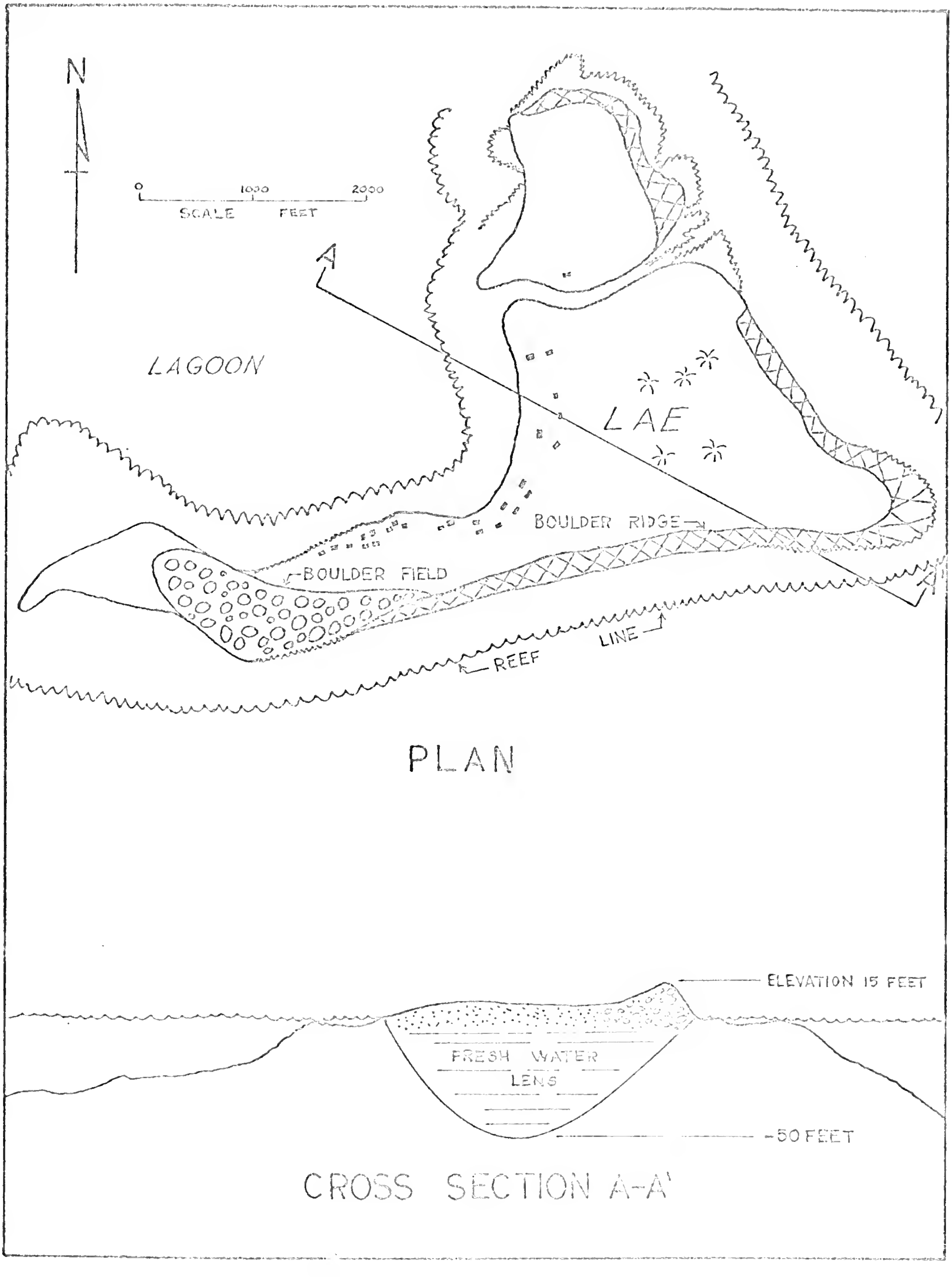

PLATE IX LAE, MARSHALL ISLANDS

INFORMATION FROM U.S. ARMY (1956)

Calms, weak variable or southeasterly winds may occur from June to September. Storms are likely to come from the south. Typhoons are rare, but do occur. Rainfall is estimated at 86 inches per year. Most of the rain falls in moderate to heavy showers of short duration during late summer and early fall.

Typically, Lae has boulder ridges and boulder fields on its seaward side, while the remainder of the island is of finer material. The highest point of the island is 15 feet above sea level along the boulder ridges; the rest of the island is between 5 and 10 feet in elevation.

Lae Island displays a permanent well-developed Ghyben-Herzberg lens. The freshest ground water appears to exist in the central part of the island. The relation of chloride content to distance from shore follows a consistent pattern, with the lowest chloride content at the greatest distance to shore. The highest water table observed in a well was 1.42 feet above mean sea level at a distance of 1,035 feet from shore. Chloride content in this well was only 10 ppm and tidal fluctuation was 0.2 feet. The chloride content in a well just 60 feet from the beach rock lined lagoon shore was only 200 ppm, well within safe limits for use.

As on all other inhabited atoll islands the coconut palm and dwelling roofs serve as catchments, augmenting the domestic ground water supply from the wells.

The High Basalt Volcanic Islands

General Nature

Basalt volcanic islands occur principally in the mid-ocean regions. They include such island groups as the Hawaiian Islands, the Samoa Islands, the Society Islands, the Galapagos Islands and the Truk Islands of the Pacific Ocean, and the islands of the Mid-Atlantic Ridge such as St. Helena and Ascension. Generally these islands are the emergent features of great broad volcanic piles lying on the deep ocean floor. The subaerial features were, in most cases, those of shield volcanoes such as are found in the Hawaiian Islands, having side slopes usually not greater than 10^{o}.

The initial form of the emerged volcanic island is modified to a great extent by erosion, movement, and subsequent volcanic activity. Occasionally post volcanic submergence may cause many smaller islands to be formed from the original volcanic island, as it has in the Truk Islands and the Hawaiian Islands. Conversely, it is possible for islands which have been formed as independent volcanic islands to be uplifted to the extent that they become a single island joined together at their bases; this apparently is the origin of Albemarle Island in the Galapagos which is now a single island, but with five volcanic high regions and five distinct species of giant tortoises (Chubb 1933).

The distinction of whether the present subaerial features were originally laid down as submarine deposits or subaerial deposits can be very significant from a hydrological viewpoint. Submarine volcanoes are

chiefly explosive, and the pyroclastic rocks from them are poorly sorted and commonly laid down with ashy shales and other sediments of low permeability. Lava flows that pour out beneath the sea are usually pillow lavas or breccias that would normally be highly permeable, but the great quantities of steam associated with such volcanoes impregnate these rocks and seal up most of the openings with secondary minerals (Stearns 1942).

In the main, the basalt volcanic islands are made of an almost endless succession of relatively thin flows of volcanic lava, with some ash and intrusive bodies, and only minor amounts of sedimentary deposits. The permeability of the volcanic mass as a whole is very great and in a class with the cavernous limestone of a karst region. Probably the greatest reason for this permeability is the extensive jointing which occurs when the lava cools rapidly. The cooled lava is also extremely brittle, breaking apart at the slightest jar. The flows of most oceanic island volcanoes have been small and therefore cooled rapidly building landmasses of great permeability. These landmasses have the following general hydrological characteristics:

1. Rapid absorption and infiltration of water
2. Small and flashy runoff
3. Scarcity of tight reservoir sites
4. Large supply of ground water
5. Very low and flat water table
6. Copious springs in the low valleys, along the coasts, and on the adjacent sea bottom.

In addition to the primary lava flows, important contributions to permeability may be made by interstitial spaces in clinker beds, cavities

between beds of various material, lava tubes, gas vesicles, and tree mold holes.

Some impermeable materials and materials of relative impermeability occur which modify and control the general permeable nature of the island. These materials include surface or buried soils and residual clays, clayey alluvial and marine deposits, beds of compact ash, igneous dikes and sills, and perhaps the dense lower parts of lava flows which cooled more slowly (Meinzer 1930).

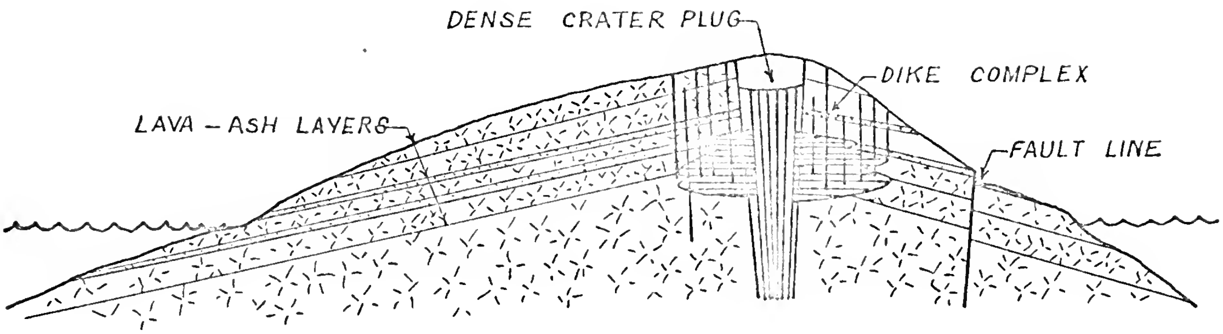

Figure 16. Generalized Section of Basalt Volcanic Island

The following is a brief description of important geologic materials found on the basalt volcanic island (illustrated on Figure 16) and their hydrologic characteristics.

Lava Flows. Basalt flows may be either a smooth flow with billowy and ropy surfaces termed pahoehoe, or a flow with clinkery or jumbled surfaces termed aa. Both are very permeable.

Dikes, sills, plugs. These are the chief shallow intrusive bodies which form in the primary flows. All have low permeability and most of them are practically impermeable.

Subaqueous lava flows. The lava which pours into bodies of water assumes properties which distinguish it from subaerial flows. Pillow lava, ball-like masses of basalt one foot or more in diameter with glass rinds, typifies such basalts. As indicated previously the interstices of such flows may be largely filled with secondary minerals making it relatively impermeable; on the other hand water may pass freely through such a deposit.

Ash. Ash may vary in size from very fine to coarse and generally covers terrain features in a uniform layer. Weathered ash and consolidated ash (tuff) is especially impermeable. The primary ash deposit will be permeable to a degree depending on the grain size.

Breccia. Volcanic breccia is the coarse product of catastrophic explosions, a pyroclastic deposit. Breccia may be consolidated into a compact impermeable mass or remain with large open voids, transmitting water freely. In some cases fault breccias aid water movement, but well-cemented gouges (from rock powder) occur in some faults impounding water as dense dikes do (Stearns 1940).

Alluvium. The alluvium on tropical islands usually contains much silt and is partly or completely weathered. This gives it a low permeability. In infrequent cases alluvium may be relatively permeable.

Beach and dune deposits. Unconsolidated deposits are very permeable; however, beach and dune deposits indurated by calcareous material may be quite impermeable (e.g. beach rock).

Talus fans. Talus fans at the base of escarpments and bluffs are composed largely of coarse but unassorted fragments. These deposits are moderately to highly permeable through which considerable water may move and be available in springs and wells.

The surface features of an island are shaped by erosive forces and late stage volcanic activity to a great extent covering and cutting through the primary volcanic deposits. Great amphitheater-headed valleys are formed and deep valleys are filled in. A fine example of extreme inversion of topography occurs on Tol in the Truk Islands. There basalt flows overlie unconformably the older fractures lavas and dikes, filling valleys that had been eroded 1000 to 2000 feet deep at the time of eruption. On Tol the original valley walls have now eroded away leaving the newer lava flow as a flat-topped ridge.

The climates and vegetation of the high volcanic islands are tremendously varied. The primary significant characteristic of all, however, is that rainfall and greenness of vegetation increase with elevation. Even on the relatively dry islands of the [illegible] group where the coastal regions receive only 3 to 4 inches of rainfall annually, the uplands above an elevation of 2000 feet receive an estimated 45 inches per year. In the Hawaiian Islands the extreme is reached with certain high regions receiving almost 500 inches of rainfall annually. In some instances, as on Ascension Island at the 2000-foot level, the island's climatic character changes abruptly from a dry, sparsely vegetated region to damp, cool, green slopes.

Natural Water Occurrence

Streams. Permeability, topography, nearness of the water table to the surface, and intensity and quantity of rainfall are the chief factors influencing runoff. On many recent basaltic cones on islands in the Pacific there is no surface drainage even though the rainfall may reach 200 inches annually or even 24 inches in a single day. All such terranes are relatively flat underlain by relatively fresh basaltic lavas or pumice, and by low water tables (Stearns 1942).

It is not unusual for streams on basaltic terrains to gain ground water for long distances, then abruptly to lose water, and finally after flowing for a distance, regain water again. This action is due to hills and valleys in the impermeable basement rock or strata.

Streams on basaltic islands in the tropics old enough to have developed soil and drainage channels are flashy and intermittent because of their steep gradients and the high permeability of the rocks. Seepage losses are extremely variable because the stream beds may, within short distances, be on fresh or weathered lava, or on relatively impermeable alluvium.

Structural [illegible] within permeable lavas also may greatly influence the regime of [illegible]. Thus, the streams on the southwest [illegible] the deeply eroded [illegible], on Oahu in the Hawaiian Islands, [illegible] intermittent, while [illegible] on the northeast side are perennial. [illegible] anomalous condition [illegible] by the streams on the northeast side [illegible] into a swarm of impermeable dikes which cut across the permeable la[illegible]

and give rise to an effluent water table (Stearns 1942).

<u>Springs</u>. Fresh water springs are a frequent occurrence along valley walls and cliffs exposing beds of material of varying degrees of permeability. Very commonly springs issue where permeable lava overlies impervious soil or ash layers. Beach springs at about sea level occur as a result of the fresh water outflow from a Ghyben-Herzberg lens.

Artesian water may occur in basaltic terrain as a result of the following conditions:

1. in counterbalance with sea water in undisturbed lava beds with an upper confining bed of impermeable sedimentary rocks, but without a lower restraining member,

2. confined within lava beds interstratified with impermeable layers and subsequently warped;

3. confined in unwarped lava beds laid down between impermeable beds with a dip sufficient to cause artesian pressure.

The greatest known artesian basin in basalt is in Oahu, Hawaii. There relatively impervious sedimentary rocks and a submerged soil blanket the permeable basalt flows along the coast and confine the water under artesian pressure, originally estimated to have been 42 feet.

Submarine springs in the waters off wet basalt islands are an interesting phenomena. In most cases they represent the outflow at the lower end of an artesian confinement system. In the Marquesas Islands it is said that a native can obtain fresh water from offshore springs by plunging into the sea with half a coconut fastened to his breast (Britannica 1964).

Of the small oceanic basalt islands, the Azores contain the largest variety of thermal springs and geysers. The mineral waters may be strongly

carbonated, ferruginous, saline, or sulphureous. Efflorescences of sulphur and alum are found near the outflow of some hot springs which may issue with a temperature near 212°F. It is interesting to note that the violence and general nature of the springs are greatly affected by changes of atmospheric pressure, the agitation being much greater during times of low barometric pressure (Walker 1886).

Lakes. Crater lakes are an occasional occurrence on the high basalt islands, being found on Easter Island, Aunuu of the Samoa Islands, San Miguel of the Azores Islands, and Tristan of the Tristan da Cunha Islands. The rather spectacular beauty of many of these high lakes causes their appearance to be noteworthy. Unfortunately many are too inaccessible to be considered a ready water supply. The development of a crater lake depends both on a wet crater summit and an impervious plug in the crater, usually of a dense lava flow such as trachyte.

On the coastal plain of dry Niihau in the Hawaiian Islands numerous playa lakes are found. During a wet year the water in these lakes is fresh, but during normal years the lakes are typical playa lakes and soon evaporate leaving salts behind. All of the lakes are only a few feet above sea level (Stearns 1947).

Swamps and marshes. Fresh water swamps and marshes are common along the inner edge of coastal flats surrounding high wet islands such as the Truk Islands (U. S. Army 1959). It would appear that this condition occurs both because of surface drainage flowing into the low areas, and the upward and outward movement of basal ground water at the edge of the land-mass.

High level swamps or marshy areas may develop on impervious flat regions of heavy rainfall. For example, Eke, a flat plateau on West Maui of the Hawaiian Islands, is essentially a cold swamp and bog. The rainfall here is 248 inches annually and the region is high (4,500 feet) but poorly drained, being underlain by dense trachyte (Stearns and MacDonald 1942).

<u>Ground water</u>. The name of "basal" ground water has been applied to all fresh water floating on sea water in permeable rocks below the water table of oceanic islands to distinguish it from perched bodies of ground water (Meinzer 1930). In the basalts, at least in regions near the coasts, the classical Ghyben-Herzberg lens may develop if the island is sufficiently wet. The basal ground water table is very flat and lies near sea level on most of the basalt islands. This fact is in contrast to the general island topography which has great relief. The ground water rises very slowly inland, so that a mile or so inland the water in wells may be only a foot or two above sea level. Accordingly the depth to basal ground water in the interior of islands is almost as great as the elevation. This severely limits the utilization of basal ground water except in deep valleys and along low coastal region. Development of the basal ground water is most efficiently accomplished by infiltration tunnels, the famous Maui wells, utilizing a skimming process so that local drawdown is minimized.

Perched ground water may be found above beds of fine grained volcanic ash, tuff or buried soils. These relatively impervious beds were laid down as continuous and fairly uniform mantles over extensive areas,

and follow the irregularities of the pre-existing surfaces. These mantles then were covered by more pervious lava flows. The percolating ground water descends to the impervious mantle and follows the pre-existing water courses as a subsurface flow. However, it must be recognized that the impervious mantle may be broken or cut through, allowing the ground water to escape to a lower level.

Recovery of such perched ground water is accomplished by running a tunnel through the upper part of the impervious ash or soil layer along a contour of its upper surface. This then will intercept the underground flowing down the slope. The roof of the tunnel must be formed of the permeable overlying lava, so that any water percolating over the ash bed may find its way into the tunnel (Meinzer 1930).

Volcanic dikes and sills may perch and dam large quantities of ground water. In some cases, complex dike and sill systems may form relatively tight open-topped compartments ideal for the collection of ground water. Systems of intersecting dikes are required to hold water, and the bottom of the compartment must consist of a relatively impervious material such as a dense volcanic sill. Such compartments may be drained rapidly if indiscriminately tapped, but if controlled can provide an excellent collection - natural storage system.

The largest supplies of perched water are found in the dike-sill complexes, and only smaller supplies are commonly available perched on beds of volcanic ash, ancient soil, or alluvium.

Typical Basalt Volcanic Island - Molokai, Hawaiian Islands

The following summation is basically from Stearns and MacDonald (1947). Exceptions are noted otherwise.

The island of Molokai is the fifth largest of the Hawaiian Islands with an area of 260 square miles. As shown on Plate X, Molokai consists of two principal parts, each a major volcanic mountain. East Molokai is a mountain built largely of thin basalt flows, with a thin cap of andesites and some trachyte, and rises to 4,970 feet altitude. Stream erosion has cut large amphitheater-headed valleys into the northern coast of East Molokai, exposing dikes and a caldera complex. West Molokai was built up by unusually fluid flows of basaltic lava and has a maximum elevation of only 1,380 feet.

Both volcanic mountains were built upward from the sea floor probably during Tertiary time. Following the close of volcanic activity stream erosion cut great canyons on East Molokai, but accomplished much less erosion on drier West Molokai. Marine erosion attacked both parts of the island producing high sea-cliffs on the windward coast. In late Tertiary or early Pleistocene time the island was submerged to a level at least 560 feet above present shore line, then re-emerged. Later changes of sea level, probably partly resulting from Pleistocene glaciation and deglaciation, ranged from 300 feet below to 100 feet or more above present sea level. Marine deposits on the southern slope extend to an altitude of at least 200 feet. Eruptions of basalt built a small lava cone at the foot of the northern cliff, forming Kalaupapa Peninsula, the site

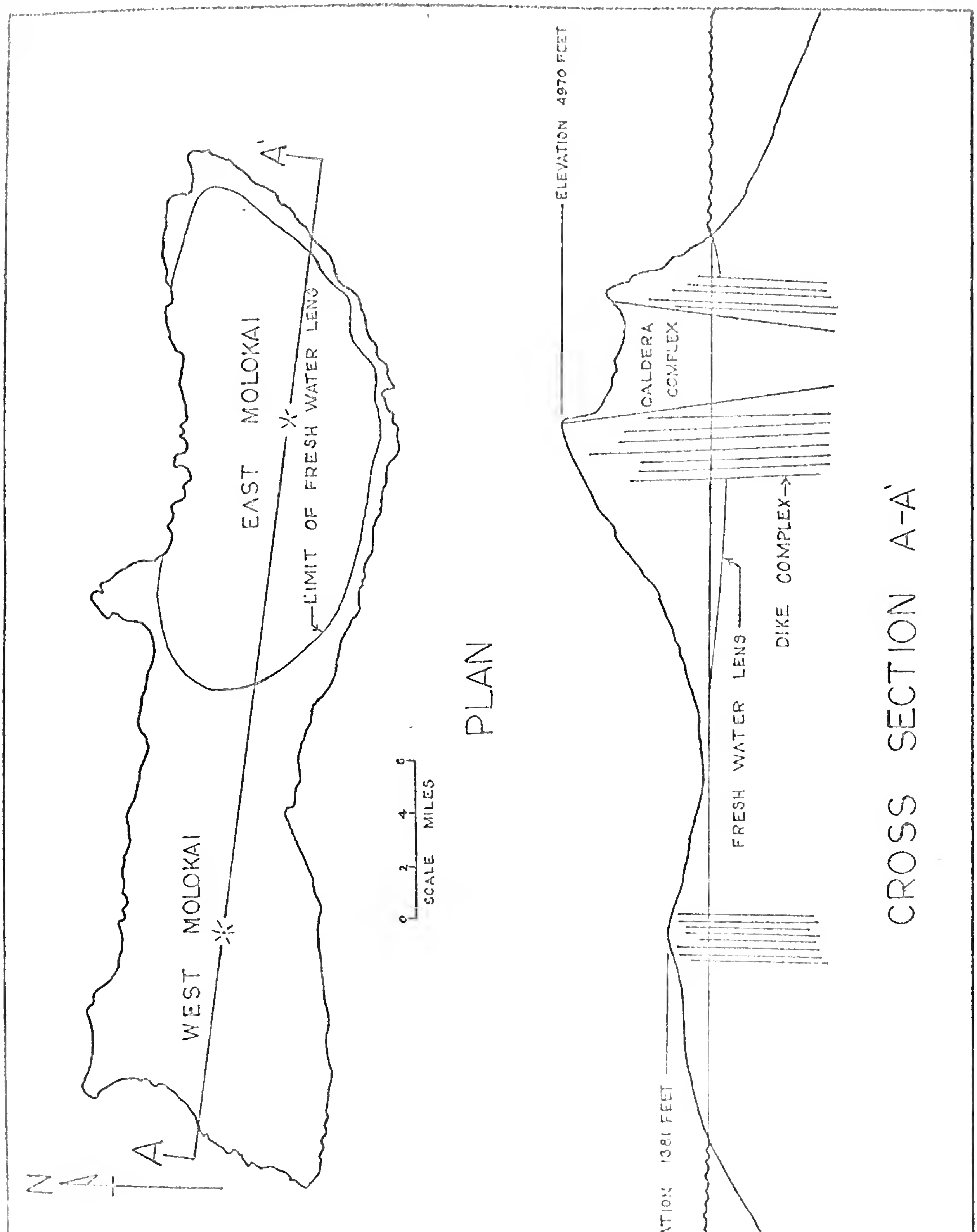

PLATE X MOLOKAI, HAWAIIAN ISLANDS

INFORMATION FROM STEARNS AND MACDONALD (1947)

of the famous leper colony; in addition a late submarine eruption built a small tuff cone off the eastern end of Molokai. Lastly, deposition of marine and fluvial sediments has built a series of narrow flats close to sea level along the southern coast. Coral reefs fringe the south coast, but few occur on the north shore.

The climate of Molokai is semitropical. The island lies in the belt of steady northeasterly trade winds. Occasional kona (southerly) winds occur in the fall and winter months. A cloud cap commonly forms over the high portion of East Molokai. The southern, or leeward slopes are largely sheltered from the trade winds, and are markedly drier and sunnier than the windward slopes.

Rainfall reaches a maximum of 150 inches annually on the summit of East Molokai. The maximum rainfall on low West Molokai is only 30 inches annually. Except for the wet northern coast of East Molokai, the coastal rainfall averages about 20 inches per year. On the leeward coast more rain may fall during a single kona storm than during all the rest of the year. Generally the summer months are the driest, averaging only about one-third the monthly rainfall of other months.

Several zones of vegetation are found ranging from semi-arid types to tropical forest growth. Along the immediate coastal zone is found a fringe of narrow bright green luxuriant growth. Then on the majority of the coast where cliff line is not encountered, is a barren zone of lava boulders and a very dry climate. Upward from this and over the low west end of the island are grasslands. As elevations increase on the eastern part of the island the grassy land gradually becomes more swampy, giving way to forest at about 2,500 feet. The upper regions are very wet and

heavily forested. Going north from the south coast upland on East Molokai the growth is dense, and one may find himself unexpectedly and abruptly on the edge of the 3000 foot high pali (Lindgren 1903).

The only perennial streams which reach the sea are those of the large valleys on the windward side of East Molokai. The permanence of these streams on the northern slope results largely from the numerous high-level springs which issue from the dike complex exposed by erosion in the big valleys. Other perennial streams on the southeastern slope, are fed largely by seepage from high-level swamps. Other streams reach the sea only at times of exceptionally high water, during, and immediately following heavy rains. All of the streams are flashy because of the steepness and high permeability of the terrain, and the intermittent character of the heavy rainfall. No perennial streams exist on West Molokai. Some streams of East Molokai are perennial in their upper courses while flowing over the poorly permeable cap of andesite lava, but become intermittent in their lower courses over the permeable basalts.

One shallow lake is perched on the andesite cap on East Molokai at about 2000 feet elevation. Extensive fresh water swamps cover large areas of the andesite cap above the 2000 feet level in the uplands of East Molokai.

Basal ground water underlies the entire island with the exception of rift zones where ground water is confined at high altitudes by dikes and is probably not in counterpoise with sea water. The Ghyben-Herzberg lens on West Molokai is brackish because of the low rainfall. Beneath most of the rest of the island, however, the basal water of the lens is of good quality.

Large numbers of basal springs issue along the shores of East Molokai; all emerge close to sea level. Submarine fresh water springs also are frequently apparent to swimmers because the escaping ground water has a lower temperature than the shallow near shore sea water. One spring discharging into an ancient Hawaiian coastal fishpond is said to have a flow of 20,000 to 30,000 gallons per day and a chloride content of 115 ppm. Submarine springs of as much as a half million gallons per day are reported.

Perched ground water is found on layers of dense lava flows, decomposed aa, clinker, soil, and ash. In dry areas the ash layers are generally sufficiently permeable to allow the small amount of water reaching them to pass on through, and descend to the basal water body. In wet areas permeability is insufficient to allow all the water to be transmitted and some of the water consequently runs off along the top of the bed in the direction of the steepest slope. In some cases springs issue from andesite lying on poorly permeable ash beds; in other cases the water issues from relatively permeable alluvium resting on a dense bed of andesite.

On East Molokai the dike complexes are sufficiently developed to perch high-level ground water. Occasionally the bottom of the diked water may be held up by sea water counterpoise, but more commonly it is due to the abundance of highly intrusive rock at the lower depths. Large amounts of fresh water at altitudes from sea level to more than 2000 feet above sea level are available in the dike complexes of East Molokai.

The Raised Limestone-Volcanic Islands

General Nature

The raised limestone-volcanic island type is the result of several different and sometimes complicated geological events. Basically the examples known are the results of one of two generalized sequences.

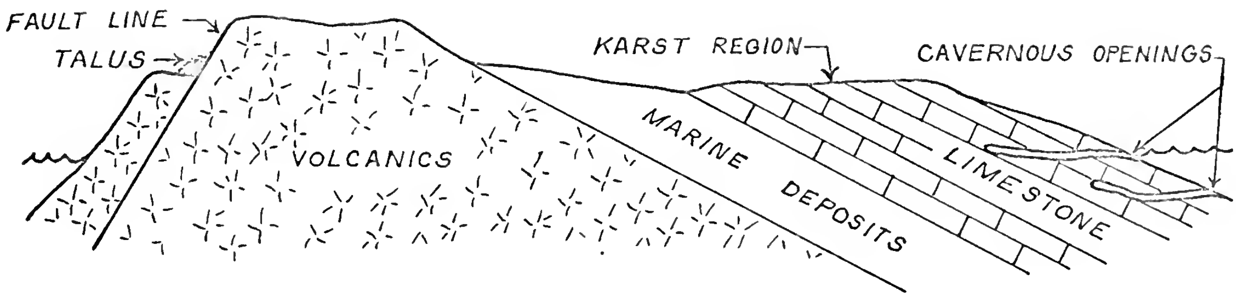

Figure 17. Generalized Section of Raised Limestone-Volcanic Island, Case 1

1. As in the case of Antigua (Figure 17) of the West Indies, the island may have been an atoll island which was tilted exposing the volcanic basement rock above sea level, and then subaerially eroded to its existing state presenting a composite surface of volcanics and limestone.

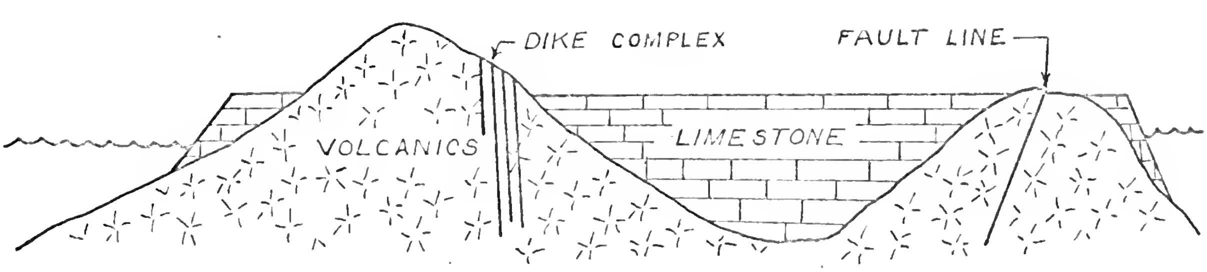

Figure 18. Generalized Section of Raised Limestone-Volcanic Island, Case 2

2. or, as in the case in the Southern Marianas, (Figure 18) the island may have been an "almost atoll" which was then uplifted revealing the limestone reef rock and lagoon deposits as broad flanking aprons on the original volcanic island(s).

Actually in both the above cases the sequence of events is much complicated by folding, faulting, repeated erosion cycles, and alternate submergence and emergence, but the basic pattern of most composite islands can be placed in one of these two categories.

All of the islands of this type known are found in island arc groups. Accordingly the volcanics are principally andesitic.

The raised limestone-volcanic island presents the charcteristics of the raised limestone island such as the "Limestone Caribbees" of the Lesser Antilles and the Tonga Islands of the Pacific, and the characteristics of the numerous high andesitic islands of the island arcs. The main hydrogeologic characteristic which is found in the composite island and which is not a major feature of the limestone or high andesitic island separately is the peculiarity of the limestone-volcanic contact. Therefore the discussion presented in this subsection will deal specifically with raised limestone-volcanic islands, but in so doing will provide the characteristics of the raised limestone island type and of the high andesite volcanic island type.

Andesitic terrain of the island arc landmasses is generally much less permeable than the basaltic terrain of mid-ocean islands. This is perhaps the most distinguishing feature of andesitic islands as compared to basaltic islands. The lack of permeability in the andesite lava flows is the primary hydrologic difference in the volcanics of the two types of islands; the characteristics of other volcanic materials, ash, breccia,

dikes, etc. are similar.

The possibility of secondary permeability in some brittle volcanic deposits must not be overlooked. The sequence of development of the raised limestone-volcanic island implies considerable movement and probable faulting and folding. In the south end (the volcanic region) of Guam the poorly sorted coarse agglomerates that normally would not be permeable carry significant water in the fissures produced by warping (Stearns 1942).

In the consideration of andesitic islands alone, the unique nature of the ground surface.of high latitude islands, such as the Aleutians, merits comment. Much of the surface of the Aleutian Islands has a mantle of relatively impermeable ash overlying dense, but fractured, bedrock. The vegetation is a thick mat of almost constantly water-soaked tundra. The top few inches of soil are a thorough blending of roots, decayed matter and ash, greatly encouraging downward percolation of water. Very little erosion occurs and streams run clear, even in the unconsolidated ash terrain. Such conditions favor slow, but continuous formation of ground water (Crandall 1963).

Most of the andesite volcanic islands and the raised limestone-volcanic islands are high enough to induce precipitation adequate for good growth of vegetation. The raised limestone-volcanic islands are tropical or subtropical producing dense jungle and thick savanna. The difference of vegetation on limestone and volcanic terrain present a marked contrast on the raised limestone-volcanic island providing ready visual indications of the underlying rock type (Cloud 1951). On Guam the limestone regions are covered with thick jungle, but the volcanic

terrain contains principally a heavy growth of sword grass.

The limestone terrain is remarkably permeable on most oceanic islands. A complete lack of surface drainage is typical. In the older regions, karst characteristics of sinkholes and pinnacle remnants may be found. Caves at many different levels representing different water tables as a result of sea level changes are frequent.

Permeability of the limestone terrain may be primary in the uplifted semi-consolidated inner lagoon deposits and secondary in the network of a joint-fracture pattern produced by diastrophic forces. The solubility of the limestone permits a modification by circulating water of permeability of both kinds. Therefore in a limestone region the permeability, undergoing progressive development, ordinarily increases with age.

Natural Water Occurrence (Andesite Volcanic Terrain)

Streams. Because of the general impermeable nature of the andesitic flows, most rainfall not taken up by vegetation or evaporated, enters the sea by surface drainage. Drainage patterns are usually well-developed in the volcanic regions. Many of the streams may begin where springs emerge from the contact of overlying limestone as is found on Guam (Cloud 1951).

Springs. Springs in the volcanics are infrequent, but may occur where bedded strata of varying permeability exist. More frequently the springs result as a result of the impermeable volcanics being overlaid by very permeable limestone.

Lakes. The imperviousness of the volcanic terrain provides the opportunity for watertight basins, but the necessary natural depressions seldom occur. Man-made lakes have been successful however.

Swamps and marshes. In the interiors of wet volcanic islands many geologic structural barriers occur which impede normal stream flow. The high surface runoff maintains swampy areas along many of the streams. Swamps or marshes also commonly occur in the contact regions where springs emerge from overlying limestone. Brackish marsh may be found at the low headlands of embayed valleys.

Ground water. In general little ground water is found in the andesite volcanic rocks, however some probably occurs in highly fractured rocks. Wells drilled in the volcanics of Guam were dry even below expected basal water level (Abplanalp 1945). The most promising water bearing strata in the volcanic terrain are the detrital accumulations in the floors of alluviated valleys. Where such valleys are embayed, bordered at one end by the sea, a partial Ghyben-Herzberg lens may develop. Beach regions along wet volcanic coasts may also develop a partial lens in the permeable sand.

Natural Water Occurrence (Limestone Terrain)

Streams. Surface runoff is virtually nonexistent in older limestone regions. Initially streams may develop, but as percolation enlarges subsurface drainage [illegible] the streams disappear into sinkholes, rapidly becoming ground water.

<u>Springs</u>. Copious springs emerge at about sea level from caves and along beach lines at the seaward edges of limestone terrain. In addition, as previously mentioned, springs are frequent at the contact of the limestone with underlying volcanic rock.

<u>Lakes, ponds and lagoons</u>. Except where sinkholes are floored with impervious alluvium, no surface water ponds on limestone terrain.

<u>Swamps and marshes</u>. Swamps and marshes are not found in limestone regions. In some limestone-volcanic islands, swampland occurs where highly eroded limestone remnants are found, but it appears that the limestone is floored by dense volcanic rock at a short depth.

<u>Ground water</u>. Almost all the rainfall reaching the surface of the limestone terrain rapidly sinks into the rock to recharge the basal ground water body. Consequently a well-developed Ghyben-Herzberg lens may normally be found within the raised limestone island or limestone portion of the raised limestone-volcanic island. The surface of the lens will generally be quite flat because of the low gradient possible in the very permeable limestone.

It should not be assumed that the ideal lens configuration exists; because of many geologic variations in the limestone, it will not. Large irregularities promote intermixing and tend to efface the zone of balance. Large openings are in a sense short circuits to the equilibrium of a Ghyben-Herzberg lens. Not only initial differences due to structural variation of calcareous accumulation, but also fissures and caves developed near sea level are important in causing important differences in

the availability of fresh ground water at various points in the lens. Caves may cross the fresh-water sea-water interface carrying highly saline water into the fresh water lens at that location, while a short distance away at the same depth the ground water may be fresh.

As in the basalt volcanic islands, horizontal infiltration tunnels reduce the risk of seriously disturbing the equilibrium of the lens. Infiltration galleries of this sort in the limestone islands begin from a point near the beach, but above the water table, driving an entrance normal to the shore down to water table, then striking out along the water table surface with a pair of infiltration tunnels 90° apart (Cloud 1951).

Bacterial contamination of ground water is commonly high in limestone areas of human occupancy. Frequently this is a more serious contamination than sea water intrusion. The surface water passes to the basal ground water lens so rapidly that little natural filtration and purification is accomplished.

Typical Raised Limestone-Volcanic Island - Guam, Mariana Islands

Guam is the largest and most southerly of the Mariana Islands. It is centered at 13°27' North latitude and 144°47' East longitude on the eastern margin of the Asiatic shelf and at the western edge of the Pacific Basin (see Figure 3). Guam is elongated northeast-southwest, and shapped rather like a peanut with a narrow waist in its center. It has a maximum length of 31 miles and ranges in width from 4-1/2 to 8 miles. Its total area is about 225 square miles. A plan and cross-section of Guam is shown on Plate XI.

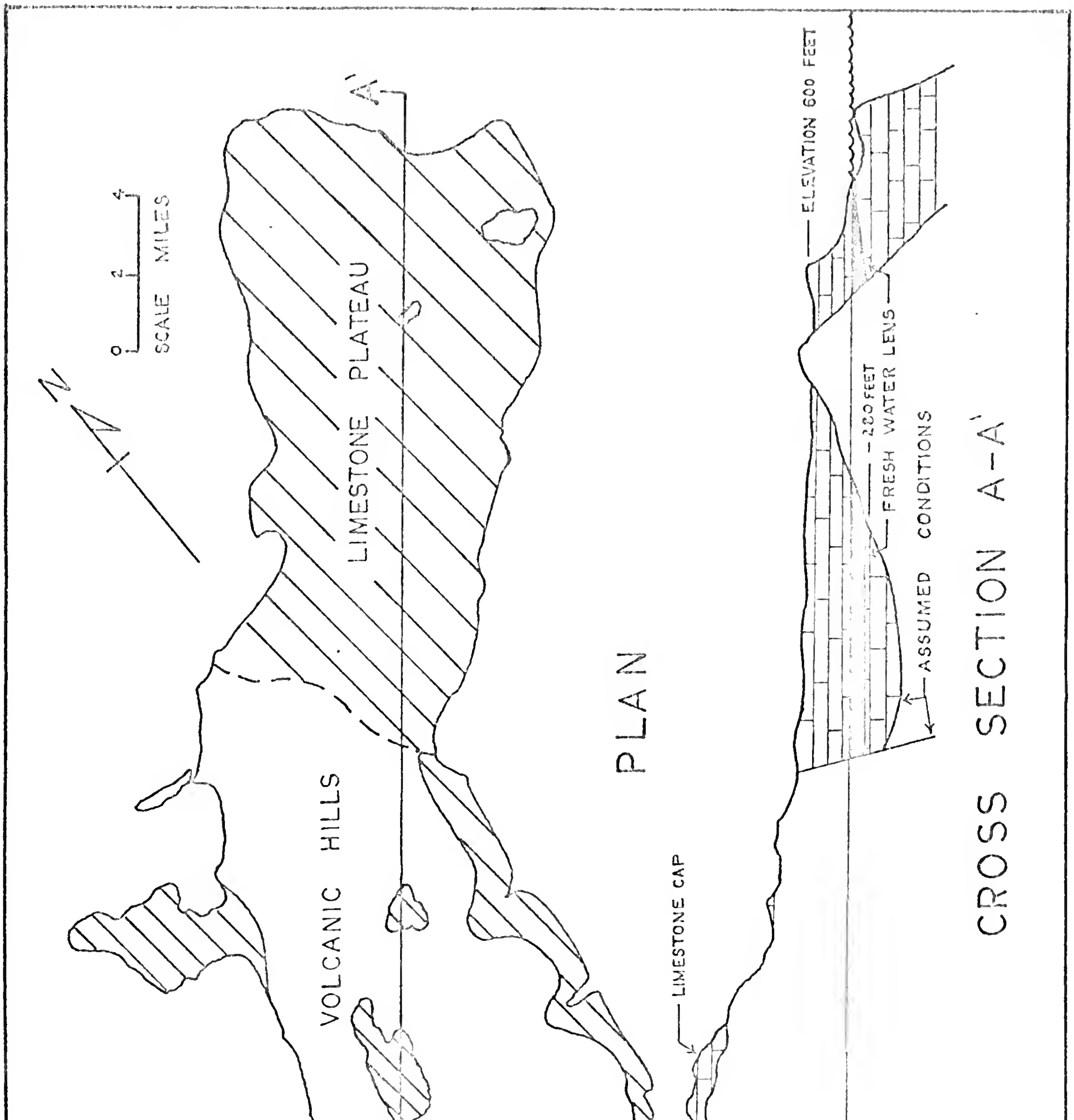

PLATE XI GUAM, MARIANA ISLANDS

INFORMATION FROM PIPER (1946)

Guam is basically a limestone veneered peak on a nearly submerged volcanic ridge. The island is sharply divided just below the waist into a northern limestone plateau and an area of higher volcanic hills to the south. A limestone wedge-like apron, similar to the limestone of the northern plateau, overlies the lower portions of the southern volcanic hills. The volcanics rising to a ridge in the west central part of the island are capped by what are probably the oldest post-volcanic limestones on the island.

The northern limestone plateau is essentially flat with a maximum elevation of 674 feet above sea level. The highest of the southern hills, Mount Lamlam rises to 1334 feet. The flat surface of the northern plateau is interrupted by the occurrence of two hills of volcanic origin.

Guam receives an average of 90 inches of rainfall annually with a rainy season in late summer and early fall. The monthly rainfall has ranged from 44.5 inches in October of 1924 to less than an inch during months of February, March, April and May. From January to March the north-east trade winds blow steady, from April through June winds are variable but easterly, in late summer the winds swing to the southeast.

A verdant growth covers most of the island. Both indigenous and imported flora grow profusely. Coconut plantations, abandoned since the Second World War are common. Indigenous growth tends to mark the geological differences on the terrain; dense head-high sharp sword grass covers the volcanic terrain while dense jungle blankets the limestone regions. One of the most geologically impressive features of the island is the marked vegetational, topographic and lithic break just south of the waist of the island.

Ancient terraces exist indicating at least ten different stands of sea level. The heavily eroded reef remnants on the beaches at the north end and eastern side of the island indicate recent emergence of the shoreline. By contrast dripstone features of stalactites and stalagmites are found in caves submerged below sea level at the northern end of the island. These features can form only above water level, hence a recent sea level rise or downward movement of the landmass is indicated. Other caves are found that have flat floors at a level five feet above sea level. Drowned stream-cut valleys are common in southern Guam. It is obvious that many changes of sea level have occurred on Guam.

Important developments in the geologic history of Guam appear to have been as follows (Stearns 1940):

1. Buildup of submarine volcanic materials, chiefly pillow lava and varied pyroclastics.

2. Cessation of volcanism.

3. Intense folding and overthrust faulting.

4. Deposition of shallow water limestone.

5. Renewed faulting.

6. Emergence of 1300 feet and subaerial erosion. The highest peak is now capped with limestone.

7. Re-submergence [illegible] to about 700 feet above present sea level during which time the northern limestone plateau was formed.

8. Complicated series of emergences and submergences ending with Guam [illegible] its present level, but with valley mouths partly drowned.

9. Minor fluctuations of the sea from about 15 feet below to about five feet above present sea level allowing caves and fringing reefs to form at these levels.

10. Final emergence of about five feet to present sea level stand.

Whereas the southern half of Guam displays a well-developed surface drainage, including several large perennial streams, surface runoff is virtually non-existent on the northern limestone plateau. Except where depressions are floored and plugged with relatively impervious soil deposits or evaporite film, most of the rainfall simply disappears through the vertical solution channels, cave crevasses, and the generally pervious body of the limestone itself. Numerous sinkholes, typical of karst terrain exist (Cloud 1951).

With respect to the development of water supplies, the geologic materials of Guam can be grouped into three categories - alluvium and beach deposits, limestone, and volcanic rocks.

The alluvium, or stream-borne deposits, is disposed chiefly in tongues which floor the lower reaches of the larger streams and in small deltas at the mouths of those streams. Its thickness is unknown but locally may be as much as several tens of feet. The alluvium consists of loose sand, silt, and gravel which in general are not well-sorted. The beds of coarse material are moderately to highly permeable, but the silt beds which make up a considerable part of the deposit are of low permeability; thus the average permeability of the deposits as a whole is generally low. Much of the alluvium is saturated with fresh water, but wells yielding more than a few gallons a minute are not likely to be obtainable except where the alluvium is unusually coarse and deep (Piper 1946).

The beach deposits consist primarily of loose calcareous sand and grit derived from the fringing coral reef. Along the southwestern shore, where backed by volcanic terrain, the beaches commonly contain [illegible]

earthy material and are only moderately permeable. Where backed by limestone cliffs they are free of earthy material and highly permeable. At least locally the beach material probably extends below sea level and contains the outer feather edge of the fresh water lens which underlies the northern limestone plateau. The beach deposits probably hold a substantial aggregate amount of fresh water (Piper 1946).

Emery (1962) found through measurements of temperature, salinity and Ca CO_3 saturation that considerable fresh water passes through the beach regions from the inland lens of fresh water. He states that; "Much of the water that escapes from the beach does so in rills, small sinuous channels that are eroded headward in the sand, particularly in the parts of the beach that are exposed only below midtide. Rills are common on most beaches, but where fresh water contributes to normal beach runoff, the rills are especially wide and deep. Velocities of .71 feet per second occur (on Guam beaches) winnowing out fine sand, leaving a concentrate of coarse grains and pebbles on the floor of the rill." Emery (1962) also reports that beach rock is rare on Guam.

Throughout the island, all the limestone seems to be at least moderately permeable, both because it is largely only moderately coherent rubble and because it is pierced by innumerable solution channels. The rain water percolates rapidly downward, forming a very considerable, but irregular, basal fresh water lens under the limestone plateau of the north; in the superimposed limestone of the southern volcanic hills, the water runs to the contact surface and then along it emerging as copious springs where the contact is exposed. In 1951 the level of fresh water near the center of the plateau and about four miles from shoreline was about seven

feet above mean low-low tide (Cloud 1951).

Piper (1946) points out that while Maui-type wells may be successful on Guam, as the length of the infiltration chambers increase, the risk of immediate sea water contamination during construction increases. This is due to the fact that the limestone of Guam is traversed by numerous solution channels which function as ground water arteries; some are large and impose virtually no resistance to the movement of water. Some such channels undoubtedly extend to the coast and contain highly saline water, deeply embaying the fresh water lens. Extreme care should be taken to monitor the incoming fresh water during the boring of an infiltration gallery to avoid opening up into a sea water channel.

Nearly everywhere the volcanic rocks are mantled by brownish, or reddish, clayey soil which is commonly at least several feet deep. This superficial mantle combined with the beneficial effect of heavy vegetation, has a high capacity to retain moisture, but small capacity to transmit water. All the underlying unweathered volcanic rocks are compact and impermeable except for openings afforded by joints and partings between beds. Thus the overall permeability and capacity of the volcanics to yield ground water are both very small.

The impervious nature of the volcanics gives rise to high surface runoff developing deep valley systems. These features make surface storage by dams feasible. A large man-made fresh water lake behind an earthfill dam in the southern volcanic hills now provides an important water supply to the Naval Base complex of Guam.

CONCLUSION

While the specific details of fresh water location, quantity and quality on a particular oceanic island can never be ascertained without extensive on-site survey and evaluation, the answers to certain basic questions can provide a reasonable understanding of the generalized hydrological situation. In the event on-site investigation is not feasible, even generalized knowledge may be invaluable; in other cases generalized knowledge may serve the immediate purpose. In many cases the mere facts of geographic location, size, and height of the island may be sufficient to enable preliminary evaluation of the probability of the occurrence of fresh water on an oceanic island.

There is certainly no substitute for real experience, but digestion of the written knowledge provided by others assuredly rates a second-best. Thus, to persons interested, but inexperienced in the consideration of the occurrence of fresh water on the oceanic island, the generalized principles herein described hopefully will provide worthwhile basic background.

Subsequent related studies of value might include the following general subjects:

The Occurrence of Fresh Water on the Small Continental Marine Island

Balancing the Hydrologic Cycle on the Small Marine Island

The Effect of Beach Rock and Subsurface Tidal Zone Barriers on the Ghyben-Herzberg Lens of Small Marine Islands

The Nature of Fresh Ground Water on the Closed Atoll Island (e.g. Clipperton Island)

Limited introductions to the foregoing suggested subjects of study have been encountered, but a fairly extensive library search of literature indicates that comprehensive treatment remains to be accomplished.

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